U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB80-118656

Effects of Flue Gas Cleaning Waste on Groundwater Quality and Soil Characteristics

(U.S.) Army Engineer Waterways Experiment Station, Vicksburg, MS

Prepared for

Municipal Environmental Research Lab, Cincinnati, OH

Aug 79

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-79-164
August 1979

Research and Development

PB80-118656

EPA

Effects of Flue Gas Cleaning Waste on Groundwater Quality and Soil Characteristics

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-79-164		PB 80 118656

4. TITLE AND SUBTITLE	5. REPORT DATE
EFFECTS OF FLUE GAS CLEANING WASTE ON GROUNDWATER QUALITY AND SOIL CHARACTERISTICS	August 1979 (Issuing Date)
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
U.S. Army Engineer Waterways Experiment Station (WES)	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
U.S. Army Engineer Waterways Experiment Station (WES) Environmental Laboratory Vicksburg, Mississippi 39180	1DC818 SOS 1 Task 27
	11. CONTRACT/GRANT NO.
	EPA-IAG-D4-0596
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Municipal Environmental Research Laboratory--Cin, OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	Final July 1976 thru Dec.1978
	14. SPONSORING AGENCY CODE
	EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer: Robert E. Landreth (513) 684-7871

16. ABSTRACT

Soil and water samples from several test borings and hydrological data were collected and analyzed for three flue gas cleaning sludge disposal sites in order to assess the extent of migration of pollutants into the local groundwater and the effects on surrounding soils. Physical testing of soils indicated that two major types of sites were included: one site was underlain by impermeable materials such as clay and shale; and two other sites underlain by relatively permeable silty sands and gravel with discontinously distributed finer materials.

At the site underlain by impermeable substrata, no change in permeability or other physical properties of the soils could be related to the presence of the disposal site. At the two sites underlain by permeable substrata, only at one could variations in permeability, dry density, water content, and percent fines be related to the presence of the disposal site. Irregular occurrences of fine-grained materials (clays and silty sands) at the other site obscured any variations in these parameters which might have been caused by the disposal site.

Sludge/ash-derived constituents were found to have migrated out of the immediate area of the pit or pond at all three disposal sites degrading the quality of the local groundwater.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Wastes, Stabilization, Leaching, Sludge Groundwater, Permeability, Pollution Sulfates, Sulfites	Leachate, Solid Waste Management Flue Gas Cleaning, Chemical Stabilization (Fixation)	13B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	132
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE PC A07 MF A01

EPA Form 2220-1 (9-73)

*U.S. GOVERNMENT PRINTING OFFICE: 1979 657 060 5383

EPA-600/2-79-164
August 1979

EFFECTS OF FLUE GAS CLEANING WASTE ON GROUNDWATER QUALITY AND SOIL CHARACTERISTICS

by

U.S. Army Engineer
Waterways Experiment Station
Environmental Laboratory
Vicksburg, Mississippi 39180

Interagency Agreement No. EPA-IAG-D4-0569

Project Officer

Robert E. Landreth
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problems.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report presents results from the field investigation of three power plant waste disposal sites to determine the effects on surrounding soils and groundwater. It provides basic data on the potential pollution of waste from coal-fired power plants and will add to the knowledge required to determine the environmental consequences of conventional land disposal of these wastes.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Soil and water samples from several test borings and hydrological data were collected and analyzed for three flue gas cleaning sludge disposal sites in order to assess the extent of migration of pollutants into the local groundwater and the effects on surrounding soils. Physical testing of soils indicated that two major types of sites were included: one site was underlain by impermeable materials such as clay and shale; and two other sites underlain by relatively permeable silty sands and gravel with discontinously distributed finer materials.

At the site underlain by impermeable substrata, no change in permeability or other physical properties of the soils could be related to the presence of the disposal site. At the two sites underlain by permeable substrata, only at one could variations in permeability, dry density, water content, and percent fines be related to the presence of the disposal site. Irregular occurrences of fine-grained materials (clays and silty sands) at the other site obscured any variations in these parameters which might have been caused by the disposal site.

Sludge/ash-derived constituents were found to have migrated out of the immediate area of the pit or pond at all three disposal sites degrading the quality of the local groundwater. The subsurface migration of the sludge/ash-derived materials was least extensive at the site underlain by impermeable substrata. At the sites underlain by sands and gravels, evidence to a typical pollution plume under and down the groundwater gradient from the disposal site was found.

Analysis of distilled water extracts and nitric acid digests of soil samples from underneath and around the sludge/ash disposal sites indicated only slight changes in soil chemistry could be attributed to the presence of the disposal pit or pond. Evidently FGC sludge/ash leachates moved through the soils and sediments without appreciable interaction or attenuation of pollutants.

This report is submitted in partial fulfillment of Interagency Agreement No. EPA-IAG-D4-0569 between the U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Solid and Hazardous Waste Research Division (EPA, MERL, SHWRD) and the U.S. Army Engineer Waterways Experiment Station (WES). Work for this report was conducted during the period of July 1976 through December 1978.

CONTENTS

Foreword iii
Abstract iv
Figures vi
Tables viii
Acknowledgment xii

1. Introduction 1
2. Conclusions 13
3. Recommendations 15
4. Materials and Methods 16
    Site selection 16
    Sampling procedures 20
    Sample handling and preparation techniques 24
    Physical testing methods 27
    Chemical analytical methods 27
5. Results and Discussion 32
    Physical testing 32
    Chemical analyses of groundwater 37
    Chemical analyses of distilled water extracts 47
    Chemical analyses of nitric acid digests 73
    Summary 88

References 93
Appendices 96

A. Sub-surface information for Site K 96
B. Sub-surface information for Site L 103
C. Sub-surface information for Site M 110

FIGURES

Number		Page
1	Sketch of a typical disposal area showing sampling plan	9
2	Topographic map of site K	18
3	Topographic map of site L	19
4	Topographic map of site M	21
5	Sketch of Hvorslev fixed piston sampler	22
6	Sketch of split spoon sampler	23
7	Variation of sulfate concentration in distilled water extracts of soil/sediment samples with elevation in borings 1 and 5 at site L	63
8	Variation of sodium concentration in distilled water extracts of soil/sediment samples with elevation in borings 1 and 5 at site L	64
9	Variation of boron concentration in distilled water extracts of soil/sediment samples with elevation in boring 1 at site L	65
10	Variation in potassium concentration in distilled water extracts of soil/sediment samples with elevation in boring 1 at site M	66
11	Variation of selenium concentration in distilled water extracts of soil/sediment samples with elevation in borings 1 at site M	67
12	Horizontal variation in chemical composition of distilled water extracts at site K	69
13	Horizontal variation in chemical composition of distilled water extracts at site K (continued)	70
14	Horizontal variation in chemical composition of distilled water extracts at site L	71

FIGURES (continued)

Number		Page
15	Horizontal variation in chemical composition of distilled water extracts at site M	72
16	Variation of iron concentration in nitric acid digests of soil/sediment samples with elevation in borings 2 and 6 at site K	86
17	Variation of boron concentration in nitric acid digests of soil/sediment samples with elevation in boring 1 and 2 at site L	87
18	Horizontal variation in chemical composition of nitric acid digests at site K	89
19	Horizontal variation in chemical composition of nitric acid digests at site L	90
20	Horizontal variation in chemical composition of nitric acid digests at site M	91
A-1	Water table map of site K	96
B-1	Water table map of site L	103
C-1	Water table map of site M	110

TABLES

Number		Page
1	Projected Annual Production of Flue Gas Cleaning Sludge in the U.S.	2
2	Composition of Some Typical FGC Sludge Solids	4
3	Typical Concentrations of Trace Elements in Several FGC Sludges and in a Variety of Coal Samples	5
4	Chemical Constituents Analytically Determined in Groundwater Filtrates, Distilled Water Extracts and Nitric Acid Digests	11
5	Summary of the Characteristics of the Three Power Generation Sites Selected for Study	17
6	Methods of Preservation of Water Extracts and Filtered Groundwater Subsamples for Chemical Analysis	26
7	Descriptions of USCS Soil Groups	28
8	Techniques Used in the Analysis of Distilled Water Extracts Nitric Acid Digests and Groundwater Filtrates	30
9	Physical Testing Data for Samples from Site K	33
10	Physical Testing Data for Samples from Site L	34
11	Physical Testing Data for Samples from Site M	35
12	Comparison of the Physical Properties of the Uppermost Soil/ Sediment Samples Collected Within and Outside the Disposal Site	36
13	Chemical Composition of Groundwater Obtained from Borings at Site K	38
14	Chemical Composition of Groundwater Obtained from Borings at Site L	39
15	Chemical Composition of Groundwater Obtained from Borings at Site M	40

TABLES (continued)

Number		Page
16	Typical Concentrations of Selected Constituents in FGC Sludge Pond Liquor and Elutriates and Surface Water Criteria for Public Water Supplies	41
17	Results of Randomization Tests for Chemical Analysis of Groundwater Samples from Sites K, L, and M	42
18	Chemical Composition of Groundwater from Wells Near Site K	44
19	Chemical Composition of Groundwater from Wells Near Site L	46
20	Chemical Composition of Groundwater from Wells Near Site M	48
21	Analyses of Distilled Water Extracts of Soil Samples from Experimental Borings at Site K	50
22	Analyses of Distilled Water Extracts of Soil Samples from Control Borings at Site K	51
23	Analyses of Distilled Water Extracts of Soil Samples from Experimental Borings at Site L	52
24	Analyses of Distilled Water Extracts of Soil Samples from Control Borings at Site L	53
25	Analyses of Distilled Water Extracts of Soil Samples from Experimental Borings at Site M	55
26	Analyses of Distilled Water Extracts of Soil Samples from Control Borings at Site M	56
27	Results of Randomization Test on Distilled Water Extracts of Soil Samples Directly Under the FGC Disposal Sites at Comparable Depths Outside the Sites	58
28	Correlation of Chemical Analyses of Distilled Water Extracts of Soils with Sample Elevation at Site K	60
29	Correlation of Chemical Analyses of Distilled Water Extracts of Soils with Sample Elevation at Site L	61
30	Correlation of Chemical Analyses of Distilled Water Extracts of Soils with Sample Elevation at Site M	62
31	Analyses of Nitric Acid Digests of Soil Samples from Experimental Borings at Site K	74

TABLES (continued)

Number		Page
32	Analyses of Nitric Acid Digests of Soil Samples from Control Borings at Site K	75
33	Analyses of Nitric Acid Digests of Soil Samples of from Experimental Borings at Site L	76
34	Analyses of Nitric Acid Digests of Soil Samples from Control Borings at Site L	77
35	Analyses of Nitric Acid Digests of Soil Samples from Experimental Borings at Site M	79
36	Analyses of Nitric Acid Digests of Soil Samples from Control Borings at Site M	80
37	Results of Randomization Test on Nitric Acid Digests of Soil Samples Directly Under the FGC Disposal Sites and at Comparable Depths Outside the Sites	83
38	Correlation of Chemical Analyses of Nitric Acid Digests of Soil Samples with Sample Elevation at Site K	84
39	Correlation of Chemical Analyses of Nitric Acid Digests of Soil Samples with Sample Elevation at Site L	85
A-1	Log of Boring 1 at Site K	97
A-2	Log of Boring 2 at Site K	97
A-3	Log of Boring 3 at Site K	98
A-4	Log of Boring 4 at Site K	98
A-5	Log of Boring 5 at Site K	99
A-6	Log of Boring 6 at Site K	99
A-7	Log of Boring 7 at Site K	100
A-8	Log of Boring 8 at Site K	101
A-9	List of Samples Examined from Site K	102
B-1	Log of Boring 1 at Site L	104
B-2	Log of Boring 2 at Site L	104
B-3	Log of Boring 3 at Site L	105
B-4	Log of Boring 4 at Site L	105

TABLES (continued)

Number		Page
B-5	Log of Boring 5 at Site L	106
B-6	Log of Boring 6 at Site L	107
B-7	Log of Boring 7 at Site L	108
B-8	List of Samples Examined from Site L	109
C-1	Log of Boring 1 at Site M	111
C-2	Log of Boring 2 at Site M	111
C-3	Log of Boring 3 at Site M	112
C-4	Log of Boring 4 at Site M	112
C-5	Log of Boring 5 at Site M	113
C-6	Log of Boring 6 at Site M	113
C-7	Log of Boring 7 at Site M	114
C-8	List of Samples Examined from Site M	115

ACKNOWLEDGMENTS

This field investigation was conducted by the Environmental Laboratory and the Geotechnical Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) under sponsorship of the Municipal Environmental Research Laboratory, Environmental Protection Agency.

The primary authors were Drs. Philip G. Malone and Larry W. Jones. Major contributions on site hydrology and geology were prepared by Mr. John H. Shamburger and Mr. Jerald D. Broughton. Significant technical input and advice were provided by Mr. Richard B. Mercer and Mr. Tommy Myers. The project was under the general supervision of Dr. John Harrison, Chief, Environmental Laboratory, Mr. Andrew J. Green, Chief, Environmental Engineering Division and Mr. Norman R. Francingues, Chief, Water Supply and Waste Treatment Group.

The guidance and support of Mr. Robert E. Landreth, Mr. Norbert B. Schomaker, and the Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency are gratefully acknowledged. The Geotechnical Laboratory performed the physical testing under the direction of Mr. G. P. Hale. The Analytical Laboratory Group performed the chemical analyses under the direction of Mr. James D. Westhoff, Dr. Donald W. Rathburn and Mr. Jerry W. Jones. The diligent and patient efforts of Ms. Rosie Lott, Ms. Connie Johnson, and Ms. Maureen Smart, typists, and Mr. Jack Dildine, senior graphics coordinator, are gratefully acknowledged. The Director of WES during the course of this study was COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

SECTION 1

INTRODUCTION

The growth of the electrical power industry coupled with the increasing use of coal as a primary fuel has resulted in a generally increased waste disposal problem for coal-fired power plants. The strict air pollution regulations regarding sulfur oxides (SO_x) emissions have caused many power plants to add stack scrubbing systems. These plants now produce a flue gas cleaning (FGC) sludge that must be disposed of along with flyash and bottom ash. Stack scrubbing is a necessary step due to the fact that sulfur dioxide (SO_2) particularly produces crop and plant damage, deterioration of many materials such as ferrous metals, marble and concrete, and increased incidence of bronchitis and lung cancer. Environmental Protection Agency (EPA) estimates have put the current total cost of SO_2 emission damage to property and people in the U.S. at $22 billion per year (1).

The flue gas cleaning systems currently being installed, and those planned for the majority of installations through 1985, are "throw-away" or non-regenerative systems in which the product generated requires permanent disposal. The end product is a fine-grained slurry of high water content called either flue gas desulfurization (FGD) or flue gas cleaning (FGC) sludge. The term flue gas desulfurization sludge usually refers to only SO_x-reaction products, while flue gas cleaning sludge refers to a more general mixture of flyash and scrubber products (2). The twenty-one power plants now equipped with FGC systems are already producing around eight million metric tons of wet sludge per year (Table 1). By 1985, when power plants producing around 100,000 megawatts of power are projected to have installed FGC equipment, over 120 million metric tons of wet sludge will have to be disposed of annually.

Three major types of "throw-away" sludge producing FGC systems are currently being developed and installed on power plants in the U. S. One uses a wet slurry of limestone ($CaCO_3$); one a wet slurry of hydrated lime ($Ca(OH)_2$); and one--the double alkali--uses a clear Na_2SO_3 solution. Although the major reaction product of all three processes is calcium sulfite hemihydrate ($CaSO_3 \cdot \frac{1}{2}H_2O$), the constituents of the sludge produced will vary widely depending upon the impurities in the scrubbing materials, the type of coal being burned, the boiler configuration and the scrubbing method used. The overall reactions of these processes are (3,4):

Limestone:

$$CaCO_3 + SO_2 + \tfrac{1}{2}H_2O \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O + CO_2$$

TABLE 1. PROJECTED ANNUAL PRODUCTION OF FLUE GAS CLEANING SLUDGE IN THE U. S. (3)

	Year		
	1977	1980	1985
Estimated on-line capacity (MW) with FGC	6500	35,000	100,000
Dry FGC sludge*	1.75	9.5	27.0
Dry ash*	2.15	11.5	33.0
Total Dry Sludge*	3.9	21.0	60.0
Water (sludge at 50% water)*	3.9	21.0	60.0
Total Wet Sludge*	7.8	42.0	120.0
Approximate total volume (m^3/yr)	4.9×10^6	2.5×10^7	7.4×10^7

* metric tons/year

Lime (hydrated):

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O + \tfrac{1}{2}H_2O$$

Double alkali:

$$Na_2SO_3 + SO_2 + H_2O \rightarrow 2\ NaHSO_3$$

$$2NaHSO_3 + Ca(OH)_2 \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O + 3/2\ H_2O + Na_2SO_3$$

The calcium can also oxidize to calcium sulfate dihydrate (gypsum) by the reaction: $2[CaSO_3 \cdot \tfrac{1}{2}H_2O] + O_2 + 2H_2O \rightarrow 2[CaSO_4 \cdot 2H_2O]$. Therefore, the final product has variable proportions of calcium sulfate and sulfite, depending upon the amount of oxygen available during the scrubbing operation.

Chemical Composition of FGC Sludges

The composition of major solid components in several FGC sludges which have been analyzed are presented in Table 2. The major component of the sludge is seen to be variable amounts of calcium sulfite and calcium sulfate, depending upon the amount of oxidation which has taken place. Oxidation (and consequently the calcium sulfate-to-calcium sulfite ratio) is usually greater in systems burning low-sulfur western coal. In all three systems, operation of the burner and FGC system can be adjusted to produce almost pure calcium sulfite sludges; or intentional oxidation can bring about the production of almost pure calcium sulfate sludges.

Variable amounts of unreacted limestone ($CaCO_3$) will be found in the limestone and dual alkali sludges, and in some lime systems where it enters as an impurity in the lime or is produced by reaction with the large amount of CO_2 in the stack gas. The amount of fly ash, the other major component in the FGC sludge, will also vary widely depending upon the ash and sulfur content of the coal burned and whether electrostatic precipitators or collectors are run ahead of the FGC system. As new FGC equipment becomes operational, many sludges may incorporate variable amounts of fly ash as the FGC systems also are excellent fly ash collectors and separate fly ash removal equipment may not be employed.

A variety of trace elements are also found in FGC sludges; typical analyses are listed in Table 3. Note the wide range of concentrations found in different sludges make generalizations as to composition difficult. The original sources of these trace elements are the coal, the lime or limestone and the makeup water. Those elements in the fuel which are not highly volatile such as chromium, manganese and nickel, will be retained in the fly ash and bottom ash. Therefore, the relative ash content controls the concentration of these elements in the sludge. On the other hand, the concentration of the highly volatile elements such as arsenic, cadmium, fluorine, mercury and selenium in the sludge depends largely upon the efficiency of their capture from the flue gas by the scrubber (9). Mercury and selenium will probably be present in the flue gas as elemental vapors and be poorly scrubbed. Assuming that the coal is the major source of trace metals and that sludge and ash

TABLE 2. COMPOSITION OF SOME TYPICAL FGC SLUDGE SOLIDS

Process	Type of coal utilized	$CaSO_3 \cdot \frac{1}{2}H_2O$ (% wt)	$CaSO_4 \cdot 2H_2O$ (% wt)	Ratio: $CaSO_4/CaSO_3$	$CaCO_3$ (% wt)	Fly ash (% wt)	Other (% wt)	(Ref.)
Limestone	Eastern	19-23	15-32	0.65-1.7	4-42	20-43		(5)
Limestone	Western	11	17	2.8	2.5	59	14% $CaS_2O_3 \cdot 6H_2O$	(5)
Lime	Eastern	13	19	2.2	0.2	60	9.8% CaS_3O_{10}	(5)
Lime	Eastern	50	6	0.12	3	41		(5)
Lime	Eastern	94	2	0.02	0	4		(6)
Dual Alkali	Western	0.2	64	400	11	9	18% $CaSO_4$	(5)
Dual Alkali	Eastern	14	52	5.1	8	7	20% $CaSO_4 \cdot \frac{1}{2}H_2O$	(7)

TABLE 3. TYPICAL CONCENTRATIONS OF TRACE ELEMENTS IN SEVERAL FGC SLUDGES (5) AND IN A VARIETY OF COAL SAMPLES (8)

Element	Conc. range in sludges (ppm)	Median conc. in sludges (ppm)	Conc. range in coal (ppm)
Arsenic	3.4-63	33.0	3-60
Beryllium	0.62-11	3.2	0.08-20
Cadmium	0.7-350	4.0	--
Chromium	3.5-34	16.0	2.5-100
Copper	1.4-47	14.0	1-100
Lead	1.0-55	14.0	3-35
Manganese	11-120	63.0	--
Mercury	0.02-6.0	1.0	0.01-30
Nickel	6.7-27	17.0	--
Selenium	<0.2-19	7.0	0.5-30
Zinc	9.8-118	57.0	0.9-600

-- = no analysis available

production equals from 5-40 percent of the coal burned on a weight basis, the trace elements will be concentrated in the sludge two to twenty times the level in the coal. The form and availability of these trace elements is also changed from that in the original coal where they are held in an organic matrix and/or as sulfides and carbonates. The trace elements appear in the sludge primarily as oxides (or in some cases in elemental form) which are more soluble and chemically reactive than sulfides or solid organic complexes. The trace elements, therefore, represent a potential pollution hazard since they can be leached from the sludge and contaminate surrounding surface water and groundwater.

Physical Properties of FGC Sludges

The physical properties of FGC sludges are of prime importance in their handling, transporting, dewatering, and leaching characteristics. The morphology and size of sludge particles varies widely as a function of the sulfur content of the coal, the way the boiler is operated, the type of particulate control employed, and the type of FGC system and the mode in which it is operated.

The most striking and troublesome physical characteristic of FGC sludges is the uniform size and form of the crystals of the calcium sulfite (10). Calcium sulfite crystals are in the form of thin platelets with 10-100 micron lateral dimensions and of 0.1 to 0.5 micron thickness. Single crystals are rare, most being found in loosely arrayed clusters. The preponderance of small, uniformly-sized crystal aggregates produces a thixotropic sludge with high moisture content and very poor settling characteristics. The high moisture content is due to the highly open, porous or sponge-type configuration of the crystal clusters. FGC sludges are not easily dewatered. For example, twenty-five hours of centrifugation at 900 times gravity in a solid-bottom centrifuge tube caused an increase from 40 percent solids to only 50 percent solids for an eastern coal, lime-scrubbing sludge (9). Slight shaking or stirring will cause the centrifuged sludge to return to a liquid or plastic state (thixotrophy). FGC sludges can present serious handling and storage problems.

The permeability of unmodified FGC sludges also varies greatly depending upon their source and fly ash content. The permeability of several samples of untreated FGC sludges were found to vary between 5×10^{-4} to 5×10^{-5} cm/ sec if gravity settled, and from 1×10^{-4} to 1×10^{-5} if compacted by vibration or by the use of a plunger (4). These moderate permeability rates are comparable to a clay or silty clay soil.

FGC sludges exhibit low compactability. When confined to a mold, sludge samples exhibit significant resistance to the action of compaction hammers, but this resistance disappears when the mold is removed. Unconfined compressive strengths are quite low, ranging from nil to 1.5 kg/sq. cm (11).

Methods of FGC Sludge Disposal

As FGC sludges began being produced, they were commonly disposed of in a manner similar to that which had been used for fly and bottom ash. Most commonly, fly ash was collected as a slurry which was pumped to settling or decanting basins where the ash settled and the liquid was decanted to a river (12). The amount of pollutants from the decanted water as well as that leaching into the groundwater from these disposal ponds could have been significant, but water quality data related to these operations are not readily available.

Presently, lagooning of mixed ash and FGC sludges is the most common method of dealing with the disposal problem (13). The sludge is usually pumped with low solids content (20-40%) into a lagoon where the solids settle out; the liquor is then reused as make-up water for the FGC process. Two major problems with this method of sludge disposal are the high levels of Ca, SO_4, SO_3, Cl, and trace metals which potentially could be leached out of the sludge bed into the local groundwater, and the physical instability of the sludge which may preclude use of the deposited sludge beds for any other purposes for an indefinite period of time (14).

One alternative which deals directly with the leaching problems is that of using lagoons which have been lined with impervious materials such as polyethylene, butyl rubber, concrete, asphalt or pozzolan-stabilized soil (13). The liners prevent the leaching of material or seepage of liquors from the disposal ponds or lagoons into ground- or surface waters. The lining of lagoons is an effective technique over the lifetime of the liner. Long-term service data applicable to sulfate/sulfite sludge containment do not exist for any liner materials although short-term experimental data have been reported (15). Lifetime estimates for different liner materials and sludge types vary from about 20 to over 50 years normal life expectancy. The major problem in the use of pond liners is their impermanence. When their integrity eventually is lost by accident or deterioration, the original problem of permanent disposal reoccurs. The use of pond liners, therefore, appears to be an effective alternative for moderately long-time periods, but not an adequate permanent disposal scheme with the technology presently available (13).

The sludge disposal techniques currently receiving the widest interest and study are those that involve chemically stabilizing or encapsulating the FGC sludges. The aims of this sludge treatment are to produce a structurally sound product (a solid, or friable, soil-like waste) that can be disposed of so that the potential for surface or groundwater pollution is minimized or eliminated (16,17).

Scope of This Study

The disposal sites selected for this study include only unlined, unstabilized power plant waste disposal ponds containing FGC sludges. The unlined ponds are considered to present the worst risk for the release of pollutants to the environment. The water released from the sludge into the soil beneath the disposal pond will be saturated with the contaminants found in the FGC sludge/ash

mixture. This water is referred to as a leachate; and the capture or absorption of potentially contaminating materials from this leachate by soil under the disposal site is referred to as attenuation.

The objectives of this study are to examine three typical, unlined FGC sludge/ash ponding or disposal operations that are situated in different geological circumstances in order to:

a) discover if changes have occurred in the chemical characteristics of the local groundwater because of the FGC sludge/ash disposal operation,

b) determine the influence of any leachate from the ponded FGC sludge/ash on the chemical characteristics and physical properties of the geologic materials directly below the landfill,

c) determine what chemical constituents present in the soil beneath the disposal site can be released into contacting water,

d) establish if a relationship exists between the depth below the disposal site and the chemical properties of the earth materials, and

e) discover if chemical characteristics of the material beneath the disposal site indicate contaminant attenuation is occurring.

To meet these objectives, a model or pattern (Figure 1) for leachate movement and attenuation was developed to provide a rationale for the sampling program. In this model precipitation falling on the disposal site saturates the sludge/ash and then percolates through the soil directly below. A variable portion of the filterable and exchangeable material in the leachate is deposited in the soil below the landfill and possibly selected constituents are released from the soil. The attenuated leachate then continues downward to the water table. Groundwater flowing under the landfill dilutes the leachate and carries the pollutants in a plume down the groundwater gradient. Based on this idealized model, borings were located in such a way as to produce:

a) groundwater from wells beneath the disposal site and from wells located both up and down the groundwater flow gradient in the area of the disposal site,

b) samples of soil from beneath the disposal site and from comparable depths outside the disposal site,

c) soil samples collected at different levels down the boreholes both outside and beneath the disposal site, and

d) samples collected near the top of the saturated zone (water table) beneath and outside the disposal site.

Physical testing of soil samples collected below the disposal site and at comparable depths outside the disposal site was undertaken to evaluate changes related to the deposition of FGC sludge. The physical characterization included

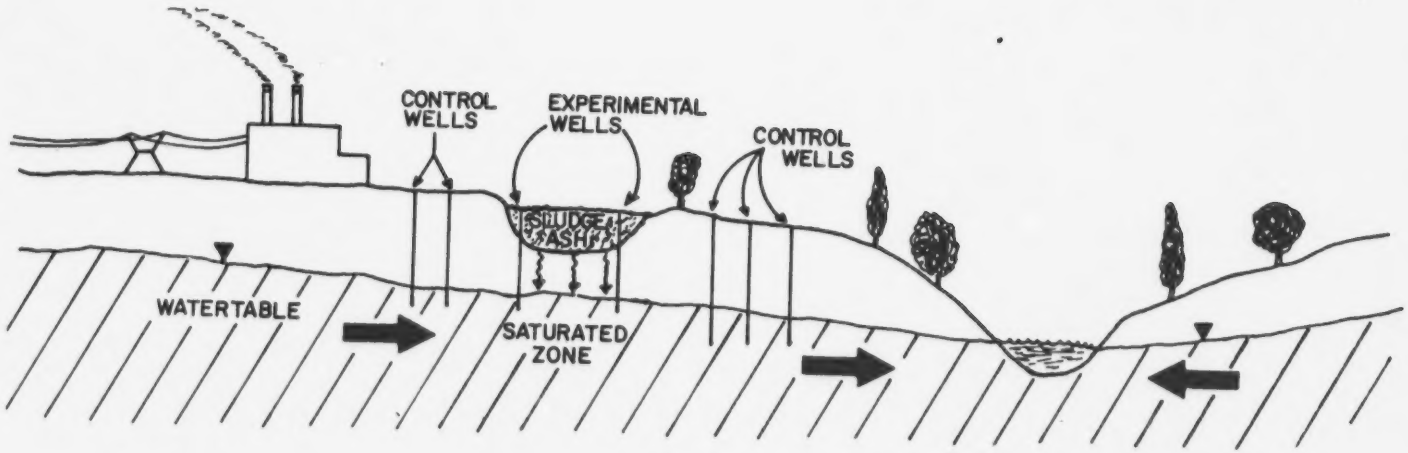

Figure 1. Sketch of a typical disposal area showing sampling plan.

percent moisture, dry density, grain-size distribution, permeability and soil classification. Randomization was used to test for significant differences in physical properties (18). Vertical variability in selected bore holes was also evaluated but the small sample sizes did not allow the use of statistical tests in this case.

The samples of groundwater collected in this study were used to indicate loss of contaminants from the sludge/ash or the soil beneath the disposal site into the local groundwater. If contaminants were moving to the water table, their concentrations should be higher beneath and downgradient from the disposal site. A list of analyses run is given in Table 4. A randomization technique was employed to assess the significance of changes in water quality. .

Soil samples from beneath the sludge/ash and from comparable depths outside the disposal site were treated in two ways. One aliquot of soil was extracted with distilled water to remove all ions that could be dislodged by water alone. A list of analyses run on this extract is given in Table 4. The distilled water extract gives a rate of release of material from the soil into the surrounding water. The water extract is assumed to represent the concentration present in water contacting the soil, not the maximum, total amount bound or confined in the soil. The distilled water leach then indicates the mobility of various ions being held in the soil. The most effective attenuation occurs when the soil beneath the sludge/ash shows an ability to accumulate a contaminant and to release the contaminant at a very slow rate. A statistical randomization technique was used to test the significance of differences observed between the composition of the distilled water extracts of soil samples collected directly beneath the sludge/ash and the composition of extracts from samples collected at comparable depths outside the disposal site. The significant results of the randomization test point out those elements at each site whose mobility in aqueous solution is effected by material from the landfill.

A second aliquot of fresh soil was digested with hot, 8N nitric acid to bring all ions not bound into silicate lattices into solution. A list of analyses run is also given in Table 4. This digest represents the total of all materials that could potentially be leached from the soil under the most severe conditions. Since it is assumed that there is no significant lateral movement of leachate through the soil above the water table, differences in composition between digests of these samples beneath and outside the disposal area can be interpreted as the loss or gain of material in the soil due to the presence of the sludge/ash. A statistical randomization technique was used to test for significant differences in composition between acid digests of soil samples collected directly below the sludge/ash and samples collected at comparable depths (and above the water table) outside the disposal site. The significant results from the randomization tests point out those elements at each site that are being added to the soil or removed from the soil by the movement of leachate from the disposal site.

If the soil beneath the disposal site was being altered by leachate from the sludge/ash, any change should be most pronounced directly beneath the sludge/ash and the magnitude of this change should decrease with depth. Samples of soil were taken at intervals down the boreholes to determine if any correlation between the concentration of materials in the soil and depth (or

TABLE 4. CHEMICAL CONSTITUENTS ANALYTICALLY DETERMINED IN GROUNDWATER FILTRATES, DISTILLED WATER EXTRACTS AND NITRIC ACID DIGESTS

Constituent	Groundwater filtrate	Water extract	Nitric acid digests
SO_4	X	X	
SO_3	X	X	
Cl	X	X	
NO_3-N	X	X	
NO_2-N	X	X	
CN	X	X	
TOC	X	X	
Ca	X	X	
Fe	X	X	X
K		X	X
Mg	X	X	
Mn	X	X	X
Na	X	X	
As	X	X	X
B	X	X	X
Be	X	X	X
Cd	X	X	X
Cr	X	X	X
Cu	X	X	X
Hg	X	X	X
Ni	X	X	X
Pb	X	X	X
Se	X	X	X
Zn	X	X	X

sample elevation) could be observed. Correlation with sample elevation was only attempted with those elements that had shown a significant contrast in concentrations from samples under and outside the disposal site. A Spearman rank correlation technique was employed (18,19). The correlation technique made it possible to see if consistent relationships could be observed between sample elevation and sample composition in borings made inside and outside the disposal site.

Samples of soil collected near the top of the saturated zone both outside and inside the disposal site were examined to see if any effects of lateral movement of leachate below the water table could be observed. Distilled water leaches and nitric acid digests of these soil samples were analyzed. Plots of analyses were prepared to assess any changes in constituents that could be related to the presence of the sludge/ash. No attempt was made to evaluate these analyses statistically because of the small sample sizes involved.

SECTION 2

CONCLUSIONS

At all three FGC/ash disposal sites (K, L, and M) investigated, indications were found that FGC sludge/ash-related materials had moved into surrounding soils and groundwater. No consistent differences in physical properties (dry density, water content, soil permeability and grain size distribution) could be detected between the soil samples taken immediately below the disposal sites and at a comparable depth outside the disposal area. No conclusive evidence could be found that the untreated sludge/ash in the pits or ponds form an effective liner.

Analysis of groundwater samples collected at each of the three sites showed some evidence of movement of FGC sludge/ash-derived materials from the disposal pit or pond into the groundwater under the site. At all sites, increased levels of some constituents could be related to the presence of the disposal pit or pond. Increased lead and mercury levels were found under the disposal pond at site K. At site L, increased concentrations in the trace metals, iron, arsenic, chromium, and lead, could be found in groundwater under the disposal pit. At site M, groundwater from beneath the disposal pond showed significant increases in sodium, chloride, and sulfate. Distilled water extracts from soil samples under and outside the disposal sites showed very little contrast. The most consistent differences observed were increases in sodium and boron in the distilled water extracts from samples directly under the disposal pits or ponds. Examination of distilled water extracts taken from soil samples at or below the local water table showed that the maximum leachable levels of sodium, sulfate, and boron were consistently found under or down the groundwater gradient from the disposal areas.

Nitric acid digests prepared from soils below and away from the disposal sites showed no consistent differences at the three sites. This suggests that changes in soil composition cannot be easily related to the passage of leachate through the soil. The only elements that appeared to be readily fixed or exchanged into soil were calcium at site K and boron at site L.

In the site investigations reported here:

a) there is no indication that FGC sludge/ash ponds or pits are self-sealing,

b) there is evidence that FGC sludge/ash constituents move into surrounding soil and groundwater,

c) there is no evidence that soils below the disposal sites are permanently retaining any FGC sludge/ash-derived materials with the exception of calcium and boron.

SECTION 3

RECOMMENDATIONS

FGC sludge/ash disposal sites can pollute surrounding groundwater and thus pose a significant threat to high-quality drinking water aquifers.

Ponds or pits for the disposal or storage of FGC sludge/ash should be engineered so as to prevent seepage from the pond or pits from moving into surrounding water and soil. There is no evidence that unaltered FGC sludge/ash in itself forms a suitable liner for a sludge and ash pond or pit.

Where the geologic and hydrologic conditions are such that contamination of usable groundwater is a possibility, plans for unsolidified sludge/ash disposal should include an artificial liner that will retain all water contacting the sludge materials. Soil attenuation is not adequate in most cases to prevent FGC sludge/ash-derived material from contaminating shallow aquifers.

An effective groundwater monitoring program should be included in plans for FGC sludge/ash disposal areas. Samples of water collected from wells adjacent to and down the groundwater gradient from the disposal site should be analyzed at regular intervals to insure the integrity of the containment system.

Additional research requirements exist particularly in the areas of evaluating the effectiveness and reliability of containment systems and designing adequate groundwater monitoring systems.

SECTION 4

MATERIALS AND METHODS

SITE SELECTION

Three electrical generating station disposal sites (containing mixed FGC sludge and ash) at different geographic areas in the central United States were selected for study. All sites were located in areas where precipitation and infiltration rates were sufficient to produce significant amounts of leachate. A brief summary of the important engineering and geologic characteristics of each site is presented in Table 5.

Some major factors effecting the character of the contaminants leaching from a disposal site are the type and amount of material placed in the site, the fossil fuel burned at the generating plant, boiler and scrubber operating conditions and the length of time the material has been in the site. Other factors effecting the character of sludge/ash leachate are oxidation-reduction conditions in the sludge and ash, and the temperatures in the disposal area. Ultimately, the concentration of pollutants in the groundwater is also related to the amount and chemical composition of local groundwater moving through the immediate area.

At site K (Figure 2), a 65-hectar pond has been receiving 31,750 metric tons per day of wet FGC sludge, fly ash and some bottom ash since the plant went on line in mid-1973. The pond can attain a maximum depth of 11 meters and has a life expectancy of 3 to 4 years as of the time of sampling. Immediately to the south of the disposal pond is a large exposed coal storage area. Runoff from the storage area also flows into the disposal pond.

The pit at site L covers 1.5 hectars with an average depth of approximately 11 meters (Figure 3). Dumping of fly ash began in the southern portion of the pit in 1968. Beginning in mid-1973, FGC sludge and fly ash were dumped in the northern part of the pit. The middle third of the pit has not received any direct dumping of sludge or ash. Before the dumping of fly ash began, the pit was free draining. Shortly after dumping started, however, the pit began to retain water and now a pond exists in the pit throughout the year. The sludge disposal pit is approximately 2 kilometers from the generating plant. The FGC sludge disposed here is filter cake with a moisture content of approximately 20%. Immediately west of the disposal area is a 40-hectar industrial tailings pond.

TABLE 5. SUMMARY OF THE CHARACTERISTICS OF THE THREE POWER GENERATION SITES SELECTED FOR STUDY

Characteristic	Site K	Site L	Site M
Unit size	820 Mw	70 Mw	130 Mw
Coal sulfur content	5.2%	3.0%	3.5%
Scrubber process type	Limestone	Lime	Limestone
Type of disposal operation	Settling pond	Pit	Settling pond
Geographic area within the U.S.	Central	Ohio Valley	Central
General geologic setting	Thin glacial outwash over bedrock	Glacial outwash (valley train deposits)	Alluvium
Mean annual precipitation	91 cm	105 cm	91 cm
Mean annual air temperature	13°C	14°C	13°C
Nature of waste	FGC sludge, fly and bottom ash	FGC sludge and fly ash	FGC sludge, fly and bottom ash
Liner used below waste material	None	None	None
Thickness of waste observed	2.49-5.49 m (avg. 3.99 m)	2.90-14.48 m (avg. 8.69 m)	2.29-4.36 m (avg. 3.33 m)
Thickness of unsaturated zone	2.44-9.00 m (avg. 6.91 m)	3.66-16.04 m (avg. 12.53 m)	4.36-7.86 m (avg. 5.72 m)
Nature of material in unsaturated zone	Clay	Clay, silty sand and gravel	Clay and silty sand
Average hydraulic conductivity below waste material	2.94×10^{-8} cm/sec	2.10×10^{-4} cm/sec	2.04×10^{-3} cm/sec
Dates of operation of site	1973 - present	1968 - present	1972 - present

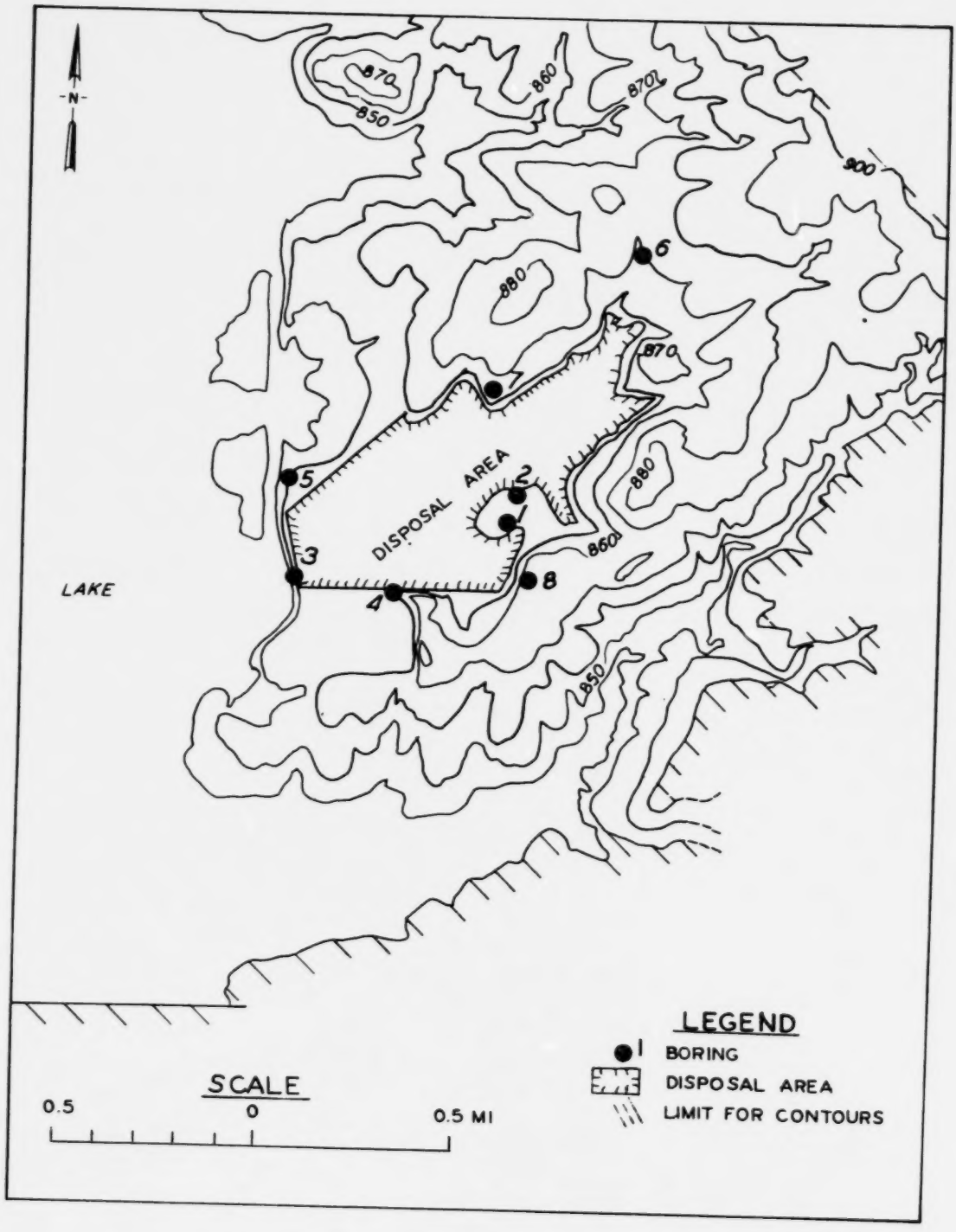

Figure 2. Topographic map of site K. 1 foot = 0.305 meters. Elevations are in ft above mean sea level.

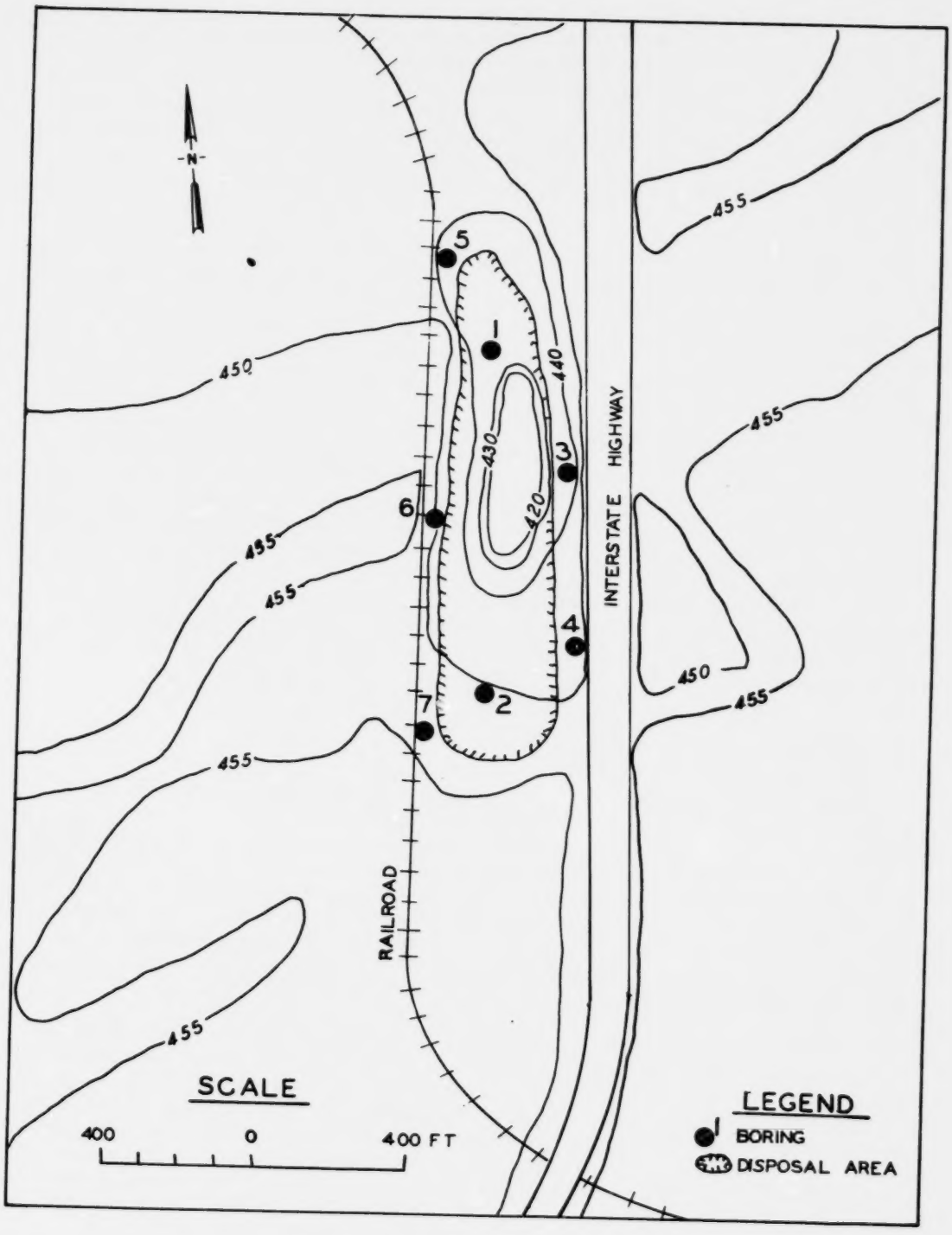

Figure 3. Topographic map of site L. 1 foot = 0.305 meters. Elevations are in ft. above mean sea level.

At site M, a 34-hectar disposal area began receiving FGC sludge, fly ash and bottom ash in 1972. Subsequent developments have resulted in off-site disposal of the majority of the bottom ash and some of the fly ash. Present practice is to discharge bottom ash into the central portion of the disposal area (see Figure 4) and fly ash and FGC sludge into the northern part of the disposal area. The southern section has received only bottom ash. A large coal storage area (approximately 30 hectars) is immediately southeast of the disposal basin.

The source of water that infiltrates the wastes is different at all three sites. At site K, the disposal pond was formed by damming a small valley that drained into the cooling lake. The water available for infiltration at this site is derived from operation of the scrubbers, plus rainfall and appreciable runoff from the surrounding hillsides. Water is recycled through the scrubber and any excess water beyond the capacity of the impoundment escapes over a spillway in the dam and into the cooling lake. Site L is an abandoned borrow pit and interrupts no natural surface drainage. The sludge as deposited contains very little water; rainfall is the only source of water available for infiltration. Site M is a series of ponds formed by constructing dikes on the floodplain. The sludge is pumped into the ponds as a slurry with high water content. After settling, the supernatant water is pumped either into a river or a sewage treatment plant. Future plans call for recycling the excess water to the scrubbers. Recycling will have no effect on the availability of water for infiltration. Permanent ponds exist at all three sites; therefore, the escape of contaminated water into the groundwater is related to the area of the bottom of the pond and the permeability of material below and at the sides of the pond, rather than the source of water.

SAMPLING PROCEDURES

A general sampling plan for all sites was generated using the model situation shown in Figure 1. This plan was modified to meet any specific requirements at each site. The general sampling plan called for a series of seven or eight borings at each disposal site. Where possible two experimental borings were to be drilled through the sludge/ash mixture and five or six control borings were to be drilled outside the disposal area. This sampling pattern would allow comparison between typical, uneffected groundwater and soil, and groundwater and soil which was in direct contact with the leachate draining from each site.

All sampling was done with a truck-mounted, rotary drill using 16.8 cm OD, hollow-stem auger. The auger, with a central plug in place, was drilled to the desired depth. The central plug was then removed and a Hvorslev fixed-piston sampler (Figure 5) or a split-spoon sampler (Figure 6) was pressed into the sediment or soil directly below the end of the auger using the hydraulic cylinders on the drill rig. In this way, an undisturbed soil or sediment sample was obtained. The split-spoon sampler was used only in cases where objects were encountered in the subsurface that could not be penetrated by the thin-walled tube (Shelby tube) on the Hvorslev sampler.

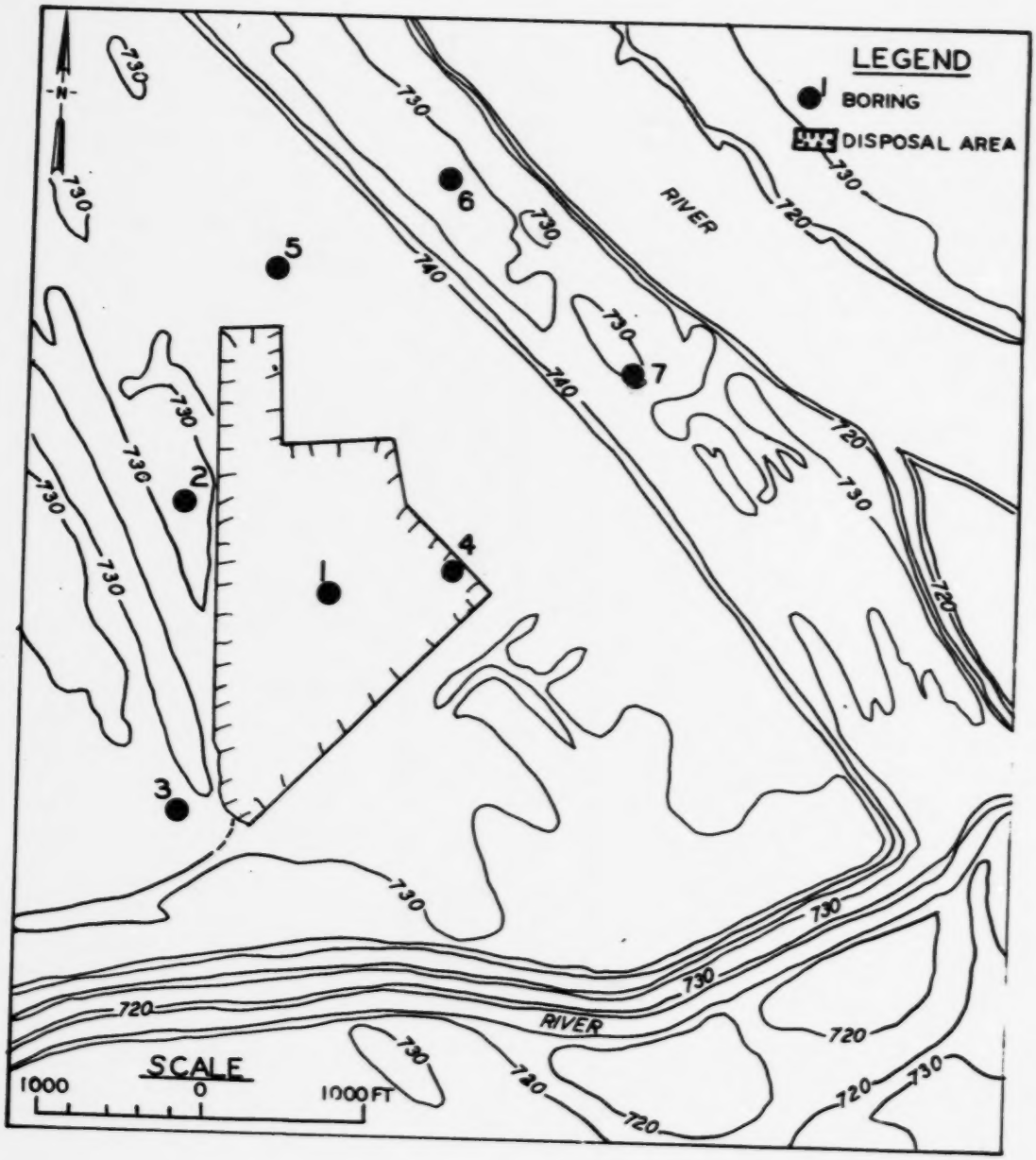

Figure 4. Topographic map of site M. 1 foot = 0.35 meters. Elevations are in ft. above mean sea level.

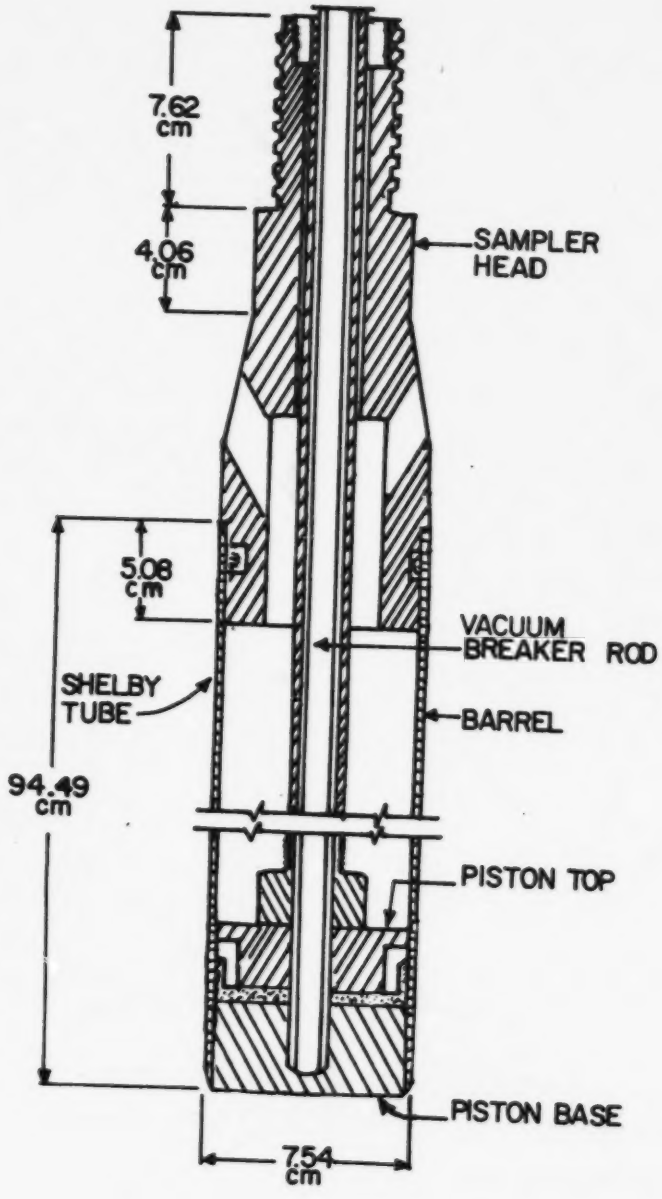

Figure 5. Sketch of Hvorslev fixed piston sampler.

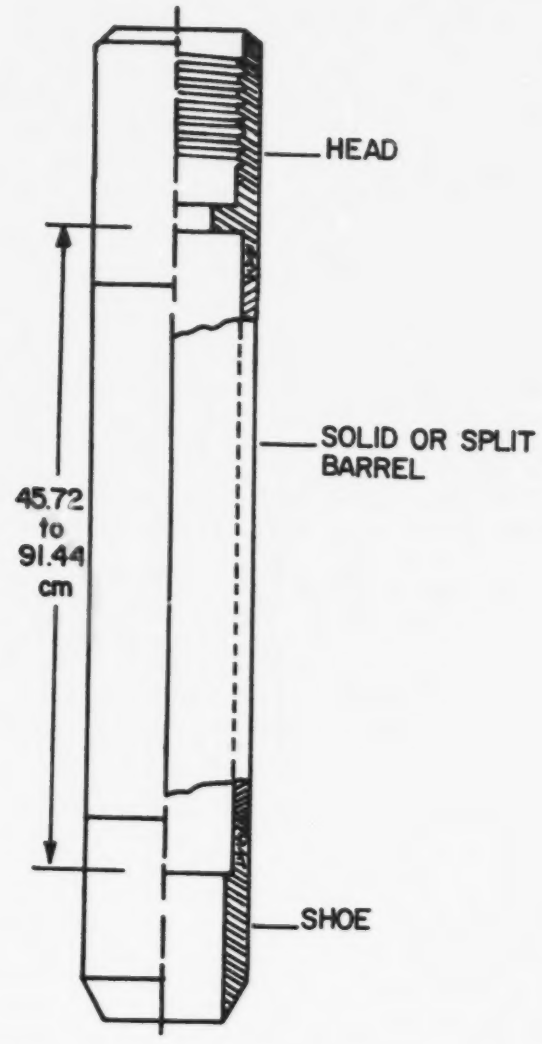

Figure 6. Sketch of split spoon sampler.

The vertical distribution of soil/sediment samples collected down the hole was arranged in a way to maximize the probability of collecting samples at two critical points in the boring; the sludge/ash-soil interface and the top of the saturated zone. Since the strongest effects of leachate on the local material should occur directly below the wastes, a sample was always taken at the sludge/ash-soil interface. Sampling was then continued at closely spaced intervals down the hole. The top of the water-saturated zone was predicted from water table measurements that had been recorded for other wells in the area and a series of closely spaced samples was taken in this interval. The borings were allowed to remain open for two to three days following the actual drilling, with the augers left in place. The auger flights served as a temporary well casing to prevent seepage from the surface from entering the well. Depth to groundwater was measured with a chalked steel tape and groundwater samples were obtained from the temporary wells by lowering a bailer into the top of the hollow-stem augers. After a groundwater sample was obtained, the auger was removed and the hole was backfilled with grout and/or bentonite to a point well above the water table. The filling was then completed with well cuttings. This was done to assure that the well would not act as a conduit for the flow of polluted water to the water table.

The locations for all borings at each FGC sludge/ash disposal site are given in Figures 2 - 4. The most probable configuration of the water table at each site, as deduced from water level measurements in the borings, is given in Figures A-1, B-1 and C-1 (in appendices). The descriptive well logs are also presented in the appendices (Tables A-2--A-9, B-2--B-8, and C-2--C-8). Tables A-10, B-9 and C-9 list all soil/sediment samples examined from each boring, giving their elevations and other relevant data.

Minor variations in the general sampling plan were necessary at sites L and M. In three instances at site L, auger wrap was used for chemical testing. These were samples 1C1, 2C1 and 5C2. Auger wrap consisted of material removed from the outside of the auger bit. Although the physical properties of auger wrap samples were disturbed, the chemical properties should be consistent with an undisturbed Hvorslev or split-spoon sample. At site M, the bearing capacity of the recently disposed material was too low to support a drill rig. Consequently, boring through the newly deposited sludge/ash material was impossible. The drill rig was placed on older, firm FGC sludge and borings 1 and 4 were made near the margin of the settling pond.

SAMPLE HANDLING AND PREPARATION TECHNIQUES

Two different types of soil samples were collected in the boring program; samples for physical testing and samples for chemical analysis. Groundwater samples were also taken from each boring for chemical analysis. The set of samples obtained for physical testing was used to determine soil class under the unified soil classification system (20), dry density, grain-size distribution, water content and permeability. These physical parameters were determined using standard engineering test procedures. This sample set was collected without disturbing the soil more than necessary. The samples were carefully packaged and sealed in coring tubes to retain the original moisture content and sample texture.

The groundwater bailed from each boring was transferred to polyethylene bottles which were labelled and packed in an insulated chest filled with crushed ice. The samples were stored under refrigeration and kept tightly capped until they were prepared for chemical analysis. The preparation consisted of centrifuging each sample at 2200 rpm for 30 minutes. The resulting supernatant was membrane-filtered through a 0.45-micron filter and split into five subsamples which were preserved as shown in Table 6.

Samples of soil for chemical analysis were collected simultaneously with the samples for physical testing, but no attempt was made to maintain the soil in an undisturbed condition. Each sample removed from the sampler or collected from the auger, was placed in a wide-mouthed polyethylene bottle, labelled and packed in an ice-filled chest. These soil samples were refrigerated during all subsequent transportation and/or storage. Two extracts were made from each soil sample; one with distilled water and one with 8N nitric acid. The materials that could be easily extracted with distilled water were considered transient and would readily be leached from the soil by dissolution in rainwater. The nitric acid digest would contain the transient materials, and also all the materials that could be solubilized by a strong, oxidizing acid. Those elements present as carbonates or sulfides, or adsorbed to clay minerals, to iron oxide or to insoluble organic materials would be freed (21); while elements in non-clay silicate lattices would be solubilized only to a minor degree (22).

For distilled water extracts, the contents of each sample bottle were mixed to assure a homogeneous sample. A 200-gram subsample of moist soil was weighed out into a 1000-ml polycarbonate centrifuge bottle and six hundred ml of distilled-deionized water was added to each. The centrifuge bottles were shaken on a rotary shaker for one hour, and then centrifuged at 2200 rpm for 30 minutes. The supernatant was filtered through a 0.45-micron membrane filter. The filtrate was split into five subsamples for chemical analysis. The subsamples were preserved as outlined in Table 6.

A second subsample consisting of 50 grams of moist soil was taken from each sample bottle for nitric acid digestion. In each digestion, the soil was weighed into a 250-ml fluorocarbon beaker and 60 ml of 8N reagent-grade nitric acid was added. The soil-acid suspension was heated to 95°C for 45 minutes and stirred every fifteen minutes. After cooling to room temperature, the suspension was filtered through a 0.45-micron membrane filter. The digested soil was washed in the filter three times with 20-ml portions of 8N nitric acid. The filtrate was quantitatively transferred to a 250-ml volumetric flask and brought up to volume with 8N nitric acid and then stored in a polyethylene bottle. No preservation procedure was necessary.

A third subsample was taken from each sample bottle to determine the moisture content of the soil. These moisture contents were used to correct subsequent chemical analyses so that soil acid digests could be expressed in milligrams per kilogram dry weight of soil.

TABLE 6. METHODS OF PRESERVATION OF WATER EXTRACTS AND FILTERED GROUNDWATER SUBSAMPLES FOR CHEMICAL ANALYSIS

Chemical species to be determined	Method of preservation
SO_4, SO_3, Cl, NO_3, NO_2	Refrigeration to 4°C
CN	Samples brought to pH 11 with NaOH
Total organic carbon (TOC)	Refrigeration to 4°C
Ca, Fe, K, Mg, Mn, Na, As, B, Be, Cd, Cr, Cu, Ni, Pb, Se, Zn	Samples acidified with HCl to pH 1
Hg	$KMnO_4$ added and samples acidified with HNO_3 to pH 1

PHYSICAL TESTING METHODS

The physical tests run on these samples included water content, sample dry density, permeability, and grain-size analysis. Data gathered from these tests and visual examination of the samples were used to classify the materials into standard soil engineering categories. All testing was done using standard soil engineering methods (23).

To determine water content, a sample taken from the sealed coring tube was weighed into a tared sample dish, dried at 110°C and weighed periodically until a constant weight was obtained.

Sample dry density (or dry unit weight) is the weight of oven-dried soil per unit volume of soil. This measurement can be made in two different ways: by trimming the soil sample into a precisely measured regular shape and drying and weighing the trimmed sample; or, by sealing the surface of a soil specimen with wax and measuring its volume by water displacement, then removing the sealing material and drying and weighing the specimen. The water displacement procedure was used with samples containing gravel or other coarse material that prevented the sample from being trimmed accurately.

Grain-size analysis was performed by sieving the dried, disaggregated soil through a standard sieve series. Standard hydrometer density measurements were run on a suspension prepared from the fraction passing the 200-mesh sieve.

Permeability measurements were made using a constant-head test system with coarse-grained soils, and a falling-head test system with fine sands or clays. In all cases standard procedures and equipment were employed (23).

The major characteristics (especially grain-size analyses and characteristics of the fine fraction) of the samples were used to classify the soils. The USCS classification system is summarized and corresponding USDA classes are given in Table 7.

CHEMICAL ANALYTICAL METHODS

The techniques used in analyzing the filtered groundwater samples, distilled water extracts and nitric acid digests are summarized in Table 8. In all cases, the samples were run within the recommended time limits for the storage of samples (24).

The analyses of groundwater samples are given in milligrams per liter of filtered sample. The water extracts are also presented in milligrams per liter of filtered extractant. The water extract represents an equilibrium or near equilibrium solution with respect to the solid phases and the adsorbed phases in the soil; therefore, the analytical data are presented on a solution basis rather than a dry weight basis. The nitric acid digests are a determination of the total acid digestible fraction; therefore, the results are presented as milligrams extracted per kilogram dry weight of soil.

TABLE 7. DESCRIPTIONS OF USCS SOIL GROUPS (20)

Group symbol	Typical group description	Example of corresponding USDA soil textural description
GW	Well-graded (poorly-sorted) gravels, gravel-sand mixtures, little or no fines	Gravel, gravelly sand
GP	Poorly-graded (well-sorted) gravels, or gravel-sand mixtures, little or no fines	Same as above
GM	Silty gravels, gravel-sand-silt mixtures	Very gravelly sand or silt loam
GC	Clayey gravels, gravel-sand-clay mixtures	Very gravelly clay loam
SW	Well-graded (poorly-sorted) sands, gravelly sands, little or no fines	Same as above
SP	Poorly-graded (well-sorted) sands, gravelly sands, little or no fines	Coarse to fine sand
SM	Silty sands, sand-silt mixtures	Loamy sand or sandy loam
SC	Clayey sands, sand-clay mixtures	Sandy clay loam or sandy clay
ML	Inorganic silts, very fine sands, clayey silts, low plasticity	Silt or silt loam
CL	Inorganic clays, low to medium plasticity, lean clays	Silty clay loam or clay loam
OL	Organic silts and organic silty clays of low plasticity	Mucky silt loam
MH	Inorganic silts, micaceous or diatomaceous fine, sandy or silty soils, elastic silts	Micaceous or diatomaceous silt

TABLE 7. DESCRIPTIONS OF USCS SOIL GROUPS (20) (continued)

Group symbol	Typical group description	Example of corresponding USDA soil textural description
CH	Inorganic clays of high plasticity, fat clays	Silty clay
OH	Organic clays of medium to high plasticity, organic silts	Mucky silty clay
Pt	Peat and other highly organic soils	Mucks and peots

TABLE 8. TECHNIQUES USED IN THE ANALYSIS OF DISTILLED WATER EXTRACTS, NITRIC ACID DIGESTS AND GROUNDWATER FILTRATES

Chemical species	Procedures and/or instrumentation*	Lowest reporting concentration (ppm)
SO_4	Standard Turbidimetric Method† in combination with a Varian Model 635 Spectrophotometer	8
SO_3	Standard Potassium Iodide-Iodate Titration method†	1
Cl	Standard Mercuric Nitrate Titration method†	5
NO_3-N	Technicon II Auto Analyzer, Industrial Method no. 100-70W±	0.01
NO_2-N	Same as above	0.01
CN	Technicon II Auto-Analyzer, Industrial Method no. 315-74W±	0.01
TOC	Determined with Envirotech Model No. DC 50 TOC Analyzer	1
Ca	Determined with a Spectrametrics Argon Plasma Emission Spectrophotometer Model II	0.03
Fe	Determined with Perkin-Elmer Heated Graphite Atomizer Atomic Absorption Unit	0.003
K	Determined with a Spectrametrics Argon Plasma Emission Spectrophotometer Model II	0.05
Mg	Same as above	0.03
Mn	Determined with Perkin-Elmer Heated Graphite Atomizer Atomic Absorption Unit	0.001
Na	Determined with Spectrametrics Argon Plasma Emission Spectrophotometer Model II	0.03

(continued)

TABLE 8 (continued)

Chemical species	Procedures and/or instrumentation*	Lowest reporting concentration (ppm)
As	Determined with a Gaseous Hydride System, Perkin-Elmer Atomic Absorption Unit	0.001
B	Determined with a Spectrametrics Argon Plasma Emission Spectrophotometer Model II	0.02
Be	Determined with a Perkin-Elmer Heated Graphite Atomizer Atomic Absorption Unit	0.0005
Cd	Same as above	0.0003
Cr	Same as above	0.003
Cu	Same as above	0.003
Hg	Determined with a Nisseisangyo Zeeman Shift Atomic Absorption Spectrophotometer	0.0002
Ni	Determined with a Perkin-Elmer Heated Graphite Atomizer Atomic Absorption Unit	0.005
Pb	Same as above	0.002
Se	Same as above	0.005
Zn	Same as above	0.014

* Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

† Standard Methods for the Examination of Water and Wastewater, American Public Health Association, New York, 13th Edition, 1971.

± Technicon Industrial Systems, Tarrytown, New York.

SECTION 5

RESULTS AND DISCUSSION

PHYSICAL TESTING

The geologic materials under a FGC disposal site are subjected to several different effects due to the presence of the waste materials. Any changes observed in the soil are probably brought about by contact with leachate saturated with respect to calcium, sulfate and sulfite. FGC sludge leachate typically has a pH between 9 and 11 and contains high concentrations of sodium and chloride. The goal of the physical testing program is to detect any changes in the soil engineering parameters which could be related to the presence of the FGC sludge/ash disposal site. Data for physical testing of soil samples from all three sites are given in Tables 9-11. The most pronounced effects should occur directly below the sludge/soil interface . For this reason Table 12 compares physical properties of the topmost soil samples taken below the disposal area with soil samples taken at comparable depths outside the disposal area. Interaction between the sludge (and its leachate) and the underlying soil would be expected to:

a) increase the dry density of the sediment (or soil) because the calcium sulfate/sulfite sludge would be filling intergranular spaces in the sediment under the disposal site;

b) increase water holding capacity in coarse-grained sediments due to the increased surface area brought about by the addition of fine-grained material;

c) decrease the permeability due to obstruction of interpore connections in the sediment; and,

d) increase the percent fines in grain-size analyses due to the infiltration of small sludge crystals or crystal aggregates.

At site K, there was no consistent influence of the disposal site on the physical characteristics measured in soil below the site. Only one sample was tested from under the disposal site and it showed a very slightly decreased dry density, increased water content and a slightly higher permeability. The percent fine-grained material was approximately the same under the site and outside the site. The usual low permeability observed in shales and clays found at this site minimizes any infiltration and therefore its effects on physical properties. At site L, a pattern of changes in physical characteristics closer to that predicted was observed. The most obvious change was the

TABLE 9. PHYSICAL TESTING DATA FOR SAMPLES FROM SITE K

Boring no.	Sample no.	Depth (m)	Dry density (g/cc)	Water content (%)	Permeability or hydraulic cond. (cm/sec)	Classification
1	P3	5.76-5.91	--	--	--	Lean clay (CL) with sand, light brown
2	P1	5.76-6.10	1.49	29.2	2.94×10^{-8}	Plastic clay (CH) with trace sand, brown
	P3	8.70-8.92	--	--	--	Silty clay (CL), dark gray
3	P1	1.74-2.15	1.72	18.5	2.55×10^{-8}	Lean clay (CL) with sand, dark brown
	P3	4.79-5.29	1.67	19.5	6.30×10^{-9}	Plastic clay (CH), brown
	P5	7.83-8.32	--	--	--	Lean clay (CL) with trace sand, dark gray
4	P1	3.26-3.75	1.73	17.7	6.20×10^{-9}	Lean clay (CL) with sand, dark brown
	P4	7.83-8.29	1.60	23.4	23.0×10^{-8}	Plastic clay (CH) with trace sand, dark gray
5	P1	1.74-2.20	1.58	24.9	4.70×10^{-9}	Plastic clay (CH) with sand, dark brown
	P2	2.65-3.12	1.71	20.0	1.03×10^{-8}	Lean clay (CL) with sand, dark brown
6	P1	2.96-3.41	--	--	--	Lean clay (CL) with trace sand, light brown
	P2	3.87-4.19	1.81	18.0	6.80×10^{-9}	Lean clay (CL) with sand, dark brown
7	P1	2.96-3.31	--	--	--	Sandy clay (CH), brown

Note: -- indicates no data available.

TABLE 10. PHYSICAL TESTING DATA FOR SAMPLES FROM SITE L

Boring no.	Sample no.	Depth (m)	Dry density (g/cc)	Water content (%)	Permeability or hydraulic cond. (cm/sec)	Classification
1	P1	3.14- 3.81	1.65	20.2	1.82×10^{-6}	Lean clay (CL) with sand, brown
2	P1	14.72-14.78	--	--	--	Silty sand (SM), light brown
	P2	15.67-15.97	1.84	9.5	4.20×10^{-4}	Gravelly sand (SP-SM), brown
3	P1	6.64- 6.95	1.78	5.7	1.18×10^{-3}	Gravelly sand (SP-SM), brown
4	P1	3.87- 4.30	1.51	9.4	1.92×10^{-3}	Silty sand (SM), light brown
	P2	8.20- 8.41	1.87	4.1	2.76×10^{-3}	Gravelly, silty sand (SM), dark brown
6	P1	4.51- 4.69	1.61	8.3	1.02×10^{-3}	Silty sand (SM), gray
	P2	12.71-12.80	--	--	--	Gravelly sand (SP), gray
7	P1	4.51- 4.91	1.53	13.2	1.13×10^{-3}	Silty sand (SM), brown

Note: -- indicates no data available.

TABLE 11. PHYSICAL TESTING DATA FOR SAMPLES FROM SITE M

Boring no.	Sample no.	Depth (m)	Dry density (g/cc)	Water content (%)	Permeability or hydraulic cond. (cm/sec)	Classification
1	P1	4.01-4.27	1.55	12.7	2.44×10^{-3}	Sand (SP), gray
	P2	5.85-6.25	1.48	13.5	7.92×10^{-4}	Silty sand (SM), gray
	P3	7.10-7.62	1.58	23.5	2.89×10^{-3}	Sand (SP-SM), gray
2	P1	0.55-1.07	1.51	8.2	2.41×10^{-3}	Sand (SP-SM), gray
	P4	4.36-4.82	1.62	22.2	2.94×10^{-3}	Sand (SP), light brown
3	P1	0.55-1.01	1.39	8.5	1.74×10^{-4}	Silt (ML), gray
	P2	1.46-1.77	1.49	13.3	7.27×10^{-5}	Sandy silt (ML), brown
	P3	3.63-4.08	1.42	29.0	4.94×10^{-4}	Silty sand (SM), brown
	P4	4.36-4.88	1.59	25.2	1.80×10^{-3}	Silty sand (SM), gray
4	P1	2.53-3.05	1.11	44.4	1.54×10^{-5}	Plastic clay (CH) with sand, dark gray
	P2	3.44-3.87	1.30	39.2	2.17×10^{-8}	Plastic clay (CH), gray
	P3	5.58-5.88	1.49	4.5	1.75×10^{-3}	Silty sand (SM), brown
	P5	7.86-8.38	1.62	22.3	2.42×10^{-3}	Sand (SP-SM), gray
5	P4	5.12-5.64	1.64	20.1	2.42×10^{-3}	Sand (SP), brown
6	P1	0.55-1.07	1.60	19.3	1.96×10^{-6}	Plastic clay (CH), gray
	P2	1.46-1.92	1.49	3.1	1.95×10^{-3}	Silty sand (SM), gray
	P3	3.57-3.96	1.60	12.2	2.29×10^{-3}	Sand (SP-SM), gray
7	P1	0.55-0.76	1.29	30.4	4.42×10^{-3}	Plastic clay (CH), gray
	P2	1.46-1.98	1.33	36.2	1.79×10^{-6}	Plastic clay (CH), gray
	P3	3.60-4.11	1.21	45.0	1.86×10^{-7}	Plastic clay (CH) with trace sand, dark gray
	P4	5.12-5.64	1.56	26.6	7.09×10^{-5}	Silty sand (SM), gray

Note: -- indicates no data available.

TABLE 12. COMPARISON OF THE PHYSICAL PROPERTIES OF THE UPPERMOST SOIL/SEDIMENT SAMPLES COLLECTED WITHIN AND OUTSIDE THE DISPOSAL SITE

Sample	Location (inside/outside)	Dry density (gm/cc)	Water content (%)	Permeability or hydraulic cond. (cm/sec)	Weight % finer than 200 mesh
K2P1	inside	1.49	29.2	2.94×10^{-8}	95
K3P1	outside	1.72	18.5	2.55×10^{-8}	
K4P1	outside	1.73	17.7	6.20×10^{-9}	89
K5P1	outside	1.58	24.9	4.70×10^{-9}	89
K6P1	oustide	--	--	--	95
K7P1	outside	--	--	--	95
					84
L1P1	inside	1.65	20.2	1.82×10^{-6}	91
L2P2	inside	1.84	9.5	4.20×10^{-4}	--
L3P1	outside	1.78	5.7	1.18×10^{-3}	8
L4P1	outside	1.51	9.4	1.92×10^{-3}	15
L6P1	outside	1.61	8.3	1.02×10^{-3}	15
L7P1	oustide	1.53	13.2	1.13×10^{-3}	27
M1P1	inside	1.55	12.7	2.44×10^{-3}	5
M4P1	inside	1.11	44.4	2.00×10^{-5}	93
M2P1	outside	1.51	8.2	2.41×10^{-3}	6
M3P1	outside	1.39	8.5	1.70×10^{-4}	99
M6P1	outside	1.60	19.3	2.00×10^{-6}	98
M7P1	outside	1.29	30.4	4.40×10^{-4}	98

Note: -- indicates no data available.

decreased permeability found in samples from beneath the disposal pit. At least one soil sample under the disposal area showed increased dry density, increased water content and a higher percentage of fines. At site M, great variability in soil type was observed at the disposal site (see Table 11) and this masked the effects that might be produced by the disposal pond. If homogenous coarse-grained sediments underlie the disposal area, it is possible to detect physical changes that can be related to the presence of the disposal site; but these effects are easily concealed by natural variations in sediment types. Although there is some suggestion of decreased permeability at the sludge-soil interface at sites L and M there is no conclusive evidence of self-sealing under the sludge pit or pond.

CHEMICAL ANALYSIS OF GROUNDWATER

The goal on the groundwater investigation is to determine if changes in chemical parameters observed in different borings at each site could be related to the position of the boring underneath or outside the disposal area. Data for chemical analysis of the groundwater samples are given in Tables 13, 14, and 15.

Published analyses of FGC sludge liquors and elutriates indicate that high and variable levels of many chemical constituents can be released to contacting waters (Table 16). As would be expected, calcium and sulfate are found at extremely high levels -- >700 and >2000 ppm respectively in typical sludge liquor samples. Calcium levels in high quality water supplies are normally around 10 ppm, and the calcium limit for water of good potability is about 200 ppm, producing a very hard water. Water quality standards (25) recommend sulfate levels of less than 250 ppm due to taste and laxative effects; ideal drinking water having none or a trace. Sludge liquors also contain trace metals which are contributed mainly by ash co-disposed with the FGC sludge. Many of these trace metals occur in quantities which are well above the levels permitted in public drinking water supplies. The most frequent problems are excessive amounts of boron, cadmium, chromium, iron, lead, manganese, and selenium (16). Chloride typically runs about 10 times (median of 2300 ppm) the drinking water standards and thus constitutes a major problem as it is always present in soluble forms which are easily leached into contacting waters.

The randomization test (Table 17) did indicate significant contrasts between groundwater samples taken underneath and outside the disposal sites. Significant increases in means between samples under the site as contrasted to outside the site could be found in mercury and lead at site K; iron, arsenic, chromium and lead at site L; and in sulfate, chloride and sodium at site M.

The experimental borings at site K were made through pads of bottom ash dumped into several feet of standing water in the pond. At this site, one of the holes under the disposal site (boring 2) showed indications of being badly contaminated by sludge pond liquor. Sulfate, iron, manganese, boron and chromium all were found at higher concentrations than are acceptable for drinking water. In contrast, boring 1 which is also within the pond and only about 100 meters from boring 2, showed no evidence of infiltrating pond liquor

TABLE 13. CHEMICAL COMPOSITION OF GROUNDWATER OBTAINED FROM BORINGS AT SITE K

Parameters	Up groundwater gradient Boring 6	Under site Boring 1	Under site Boring 2	Down groundwater gradient Boring 3
SO_4	900	180	1400	42
SO_3	1	<1	1	<1
Cl	10	5	5	5
NO_3-N	0.02	0.06	0.03	0.11
NO_2-N	<0.01	0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01
TOC	10	5	12	6
Ca	95.00	49.00	59.00	65.00
Fe	0.100	0.055	0.534	0.079
Mg	70.00	18.00	39.00	20.00
Mn	0.117	0.009	4.430	0.123
Na	310.00	82.00	23.00	95.00
As	ND	ND	ND	ND
B	0.34	0.22	1.07	0.03
Be	0.0390	0.1130	0.0280	0.0390
Cd	0.0004	<0.0003	0.0003	<0.0003
Cr	<0.003	<0.003	0.076	<0.003
Cu	<0.003	<0.003	<0.003	<0.003
Hg	<0.0002	0.0017	0.0004	<0.0002
Ni	0.456	0.251	1.360	0.365
Pb	0.002	0.002	0.003	<0.002
Se	ND	ND	ND	ND
Zn	0.170	0.082	0.090	0.170

Note: All values are in mg/ℓ.

ND = Not determined.

TABLE 14. CHEMICAL COMPOSITION OF GROUNDWATER OBTAINED FROM BORINGS AT SITE L

Parameters	Up groundwater gradient		Under site		Down groundwater gradient		
	Boring 3	Boring 4	Boring 1	Boring 2	Boring 5	Boring 6	Boring 7
SO_4	249	139	ND	ND	ND	1399	299
SO_3	<1	<1	ND	ND	ND	<1	<1
Cl	35	30	ND	ND	ND	50	35
NO_3-N	5.08	6.60	ND	ND	ND	7.25	3.42
NO_2-N	0.05	0.06	ND	ND	ND	0.04	0.04
CN	0.01	0.01	<0.01	<0.01	<0.01	0.07	ND
TOC	14	12	19	10	29	22	ND
Ca	215.00	169.10	325.00	272.00	235.00	432.00	212.4
Fe	<0.003	<0.003	0.117	0.103	<0.003	<0.003	<0.003
Mg	71.90	68.80	64.60	50.90	93.10	160.00	64.80
Mn	9.230	6.390	1.290	2.81	3.780	12.000	2.070
Na	22.40	18.90	18.60	60.00	22.70	30.20	31.90
As	<0.005	<0.005	0.008	0.006	0.008	<0.005	<0.005
B	0.76	1.56	1.99	3.48	1.93	4.22	4.71
Be	0.0050	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cd	0.0003	<0.0003	0.0008	<0.0003	<0.0003	0.0007	0.0003
Cr	<0.003	<0.003	0.003	0.003	<0.003	<0.003	<0.003
Cu	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Hg	ND	ND	<0.0002	<0.0002	ND	ND	<0.0002
Ni	0.082	0.054	0.024	0.021	0.048	0.047	0.029
Pb	<0.002	<0.002	0.008	0.005	<0.002	<0.002	<0.002
Se	0.005	<0.005	<0.005	0.005	<0.005	0.005	0.007
Zn	<0.014	<0.014	0.014	0.019	0.020	<0.014	<0.014

Note: All values are in mg/l.

ND = Not determined.

TABLE 15. CHEMICAL COMPOSITION OF GROUNDWATER OBTAINED FROM BORINGS AT SITE M

Parameters	Up groundwater gradient		Under site		Down groundwater gradient		
	Boring 2	Boring 3	Boring 1	Boring 4	Boring 5	Boring 6	Boring 7
SO_4	124	69	259	499	54	99	219
SO_3	<1	<1	<1	<1	2	<1	<1
Cl	15	10	45	30	<5	15	15
NO_3-N	9.24	4.10	0.61	0.12	0.68	0.49	0.14
NO_2-N	0.09	0.13	0.06	0.03	0.05	0.04	0.04
CN^2	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	11	10	18	13	13	18	21
Ca	158.30	177.80	121.60	221.00	148.70	151.90	225.00
Fe	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Mg	34.00	47.40	2.80	11.50	43.50	41.90	94.10
Mn	0.716	1.740	<0.002	0.566	1.130	1.350	2.34
Na	8.20	10.60	87.70	81.40	11.70	21.50	61.70
As	<0.005	0.005	<0.005	0.006	0.006	0.005	0.005
B	0.32	0.22	0.64	4.40	0.25	0.84	0.82
Be	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cd	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Cr	<0.003	<0.003	0.014	<0.003	<0.003	<0.003	<0.003
Cu	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Hg	0.0004	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Ni	0.008	0.011	0.014	<0.005	0.011	<0.005	<0.005
Pb	0.009	0.002	0.006	<0.002	0.002	0.002	<0.002
Se	0.009	0.035	<0.005	0.011	<0.005	0.011	0.008
Zn	0.014	<0.014	<0.014	0.041	0.090	0.018	<0.014

Note: All values are in mg/ℓ.

ND = Not determined.

TABLE 16. TYPICAL CONCENTRATIONS OF SELECTED CONSTITUENTS IN FGC SLUDGE POND LIQUOR AND ELUTRIATES (3) AND SURFACE WATER CRITERIA FOR PUBLIC WATER SUPPLIES (25,26)

Constituent	Eastern coal median conc. (ppm)	Western coal median conc. (ppm)	Maximum permissible level (ppm)
Arsenic	0.020 (15)*	0.009 (7)*	0.05
Beryllium	0.014 (6)	0.013 (7)	--
Boron	41.0 (1)	8.0 (1)	1.0
Cadmium	0.023 (11)	0.032 (11)	0.01
Calcium	700 (15)	720 (6)	--
Chromium	0.020 (15)	0.08 (7)	0.05
Cobalt	0.35 (3)	0.14 (2)	--
Copper	0.015 (15)	0.20 (7)	--
Iron	0.026 (5)	4.3 (2)	0.3
Lead	0.12 (15)	0.016 (7)	0.05
Manganese	0.17 (8)	0.74 (6)	0.05
Mercury	0.001 (10)	<0.01 (7)	--
Molybdenum	5.3 (1)	0.91 (1)	--
Nickel	0.13 (11)	0.09 (6)	--
Selenium	0.11 (14)	0.14 (7)	0.01
Sodium	118 (6)	--	--
Zinc	0.046 (15)	0.18 (7)	--
Chloride	2,300 (9)	--	250
Fluoride	3.2 (9)	1.5 (3)	1.0
Sulfate	2,100 (13)	3,700 (7)	250
Total dissolved solids	7,000 --	12,000 (3)	500

* Total number of observations recorded.

TABLE 17. RESULTS OF RANDOMIZATION TESTS FOR CHEMICAL ANALYSIS OF GROUNDWATER SAMPLES FROM SITES K, L AND M

Parameters	Site K	Site L	Site M
SO_4	NS	ND	S(increases)
SO_3	NS	ND	BDL
Cl	S(decreases)*	ND	S(increases)
NO_3-N	NS	ND	NS
NO_2-N	BDL	ND	NS
CN	NS	S(decreases)	S(decreases)
TOC	NS	NS	NS
Ca	S(decreases)	NS	NS
Fe	NS	S(increases)	NS
Mg	NS	S(decreases)	S(decreases)
Mn	NS	S(decreases)	S(decreases)
Na	S(decreases)	NS	S(increases)
As	NS	S(increases)	NS
B	NS	NS	NS
Be	NS	BDL	NS
Cd	NS	NS	NS
Cr	BDL	S(increases)	BDL
Cu	BDL	BDL	NS
Hg	S(increases)	ND	BDL
Ni	NS	S(decreases)	NS
Pb	S(increases)	S(increases)	NS
Se	ND	NS	NS
Zn	S	NS	NS

NS = Not significant at 80% confidence level.

S = Significant at 80% confidence level.

BDL = Below detection limits.

ND = Not determined.

*Refers to increase or decrease of constituent under disposal site relative to outside.

and was below the maximum permissible level for public water supplies for all constituents measured (25,26).

The groundwater sampling program at site K was complicated by impervious rock units and a low water table associated with the Pennsylvanian shales and limestones in the area. Five of the holes drilled failed to reach the saturated zone before encountering rock units that could not be penetrated by the auger. The well bored as a control up the postulated groundwater gradient from the disposal pond (boring 6) appears to have encountered a local, saturated zone created by infiltration of pond liquor into the colluvium and weathered shale forming the valley wall. The water level (elevation 260.06 m) measured in the well is 2.37 meters below the elevation of the surface of the disposal pond, suggesting the ponding has caused invasion (for distance of at least 200 meters) into the local colluvial materials.

In boring 3, which is down the apparent groundwater gradient from the disposal pond, levels for most chemical constituents are present in lower concentrations than that observed for boring 6 (the upgradient control hole). Boring 3 is in close proximity (approximately 10 meters distance) to the margin of a 1052-hectar cooling lake. Uncontaminated water from the lake could easily infiltrate the boring and bring about the low concentrations found in this groundwater sample. The elevation of water in the well is less than a meter below the level of the lake surface suggesting an hydraulic connection.

Of the two experimental borings through the disposal pond, one (boring 2) yielded a groundwater sample that approaches pond liquor in composition (see Table 16); while groundwater from the other (boring 1) appears to be much less effected by the surrounding waste. In fact, groundwater from boring 1 is (with the exception of sulfate content) within the range of composition observed for groundwater from other wells in the county (Table 18). The sulfate level was 190% higher than the highest value obtained from local water wells. The difference in water levels observed in experimental borings 1 and 2 (approximately 7 m) suggests no hydraulic connection exists between the two wells. The materials in the disposal pond include ash and FGC sludges. Sludge was noted, mixed with ash, in the hole during the drilling of boring 2. Boring 1, on the other hand, penetrated only ash and clay. The differences in water samples may be related to this inhomogeneous distribution of FGC sludge and ash in the disposal pond. The only trace metals that the randomization test indicated were sigificantly increased in groundwater below the disposal pond are lead and mercury; two elements probably associated with ash, present in both experimental borings.

In summary, at site K, only the groundwater in borings 6 (control boring) and 2 (experimental boring) show the effects of contamination from disposal pond liquor. The lack of wider contamination is probably due to the low permeability of the ash, clay and shale at and around boring 1, and the lack of permeability in the clay and shales under the disposal pond and between the pond and boring 3.

At site L, the experimental borings were made directly through the surface of the solid sludge that had been dumped into the pit. The material had

TABLE 18. CHEMICAL COMPOSITION OF GROUNDWATER FROM WELLS NEAR SITE K

Local well number	31	36	3	19	32	29	Range
Conc. (mg/ℓ)							
SO_4	62.0	52.0	4.1	30.0	41.0	30.0	4.1-62.0
Cl	5.0	14.0	1030.0	6.0	49.0	8.0	5.0-1030.0
F	0.3	0.1	0.1	0.1	0.8	0.4	0.1-0.8
CO_3	0	0	0	0	0	0	0
HCO_3	127	254	405	310	566	239	127-566
NO_3	12.0	8.9	8.0	44.0	0.4	6.2	0.4-44.0
SiO_2	12.0	17.0	17.0	7.5	12.0	12.0	7.5-17.0
Ca	43	99	315	114	28	65	28-315
Fe	0.18	0.05	0.04	0.24	2.30	0.15	0.04-2.30
K	ND	ND	ND	ND	ND	ND	
Mg	13.0	5.1	69.0	5.7	13.0	15.0	5.1-69.0
Mn	0.00	0.00	0.00	0.00	ND	0.00	0
Na	12.0	9.7	330.0	9.9	209.0	9.4	9.4-330.0

ND = Not determined.

sufficient bearing capacity to support the drill rig. No standing water was present. At this site, all of the wells show some effects of pollutants. Even groundwater from upgradient borings show high levels of nitrate, manganese and boron. In the case of nitrate and manganese most of the groundwater samples analyzed in this study exceeded the levels obtained from other wells in the general area that intercept the same surface aquifer (Table 19). Groundwater from all the borings made in this investigation exceeded the concentration limits recommended for public water supplies for manganese and all except boring 3 exceeded the limits for boron. These high background levels are probably due to materials added to the groundwater by other industrial disposal pits in the area.

The most severe groundwater contamination at site L was not observed in the borings directly through the disposal pit (borings 1 and 2), but rather in the borings made down the groundwater gradient from the pit (borings 5, 7 and expecially 6). The randomization test points out significant differences between groundwater from the borings inside and outside pit; therefore in this case, the results are not as helpful in pointing out the materials leaching from the pit as they might be if the maximum pollutant concentrations had occurred (as would be expected) in borings through the waste. The randomization test did show significantly increased concentrations of iron, arsenic, chromium and lead in groundwater directly under the disposal pit. With the exception of calcium, magnesium and manganese the concentrations of all elements measured directly under the disposal area were within the range observed for water from wells drilled into this same aquifer (Table 19). Calcium in water from directly under the disposal pit was only 30% higher than the highest values obtained from local water wells. Concentrations of magnesium increased by about 40% under the disposal area and manganese increased by 3%. In the down gradient holes, calcium levels increased by 73% over the highest values for local water wells. Concentrations of magnesium increased by 208% and manganese by 344%. Sulfate levels, where measured, exceeded limits for public water supply and were up to 191% above highest level in local water wells.

The results of groundwater analyses at site L were unexpected in that the contaminants reached maximum levels in wells down the groundwater gradient from the disposal pit. These high levels may be due to the flow pattern involved in movement of groundwater through and under the disposal site. The borings in the pit are approximately centered so that the half of the disposal pit up the groundwater flow gradient is the only part contributing pollutants to the groundwater collected from the experimental borings. The down gradient control holes, on the other hand, (especially boring 6) are located on the edge of the disposal pit and receive water contaminated during travel under the entire width of the pit. In addition, water washing across the surface of the sludge and infiltrating at the edge of the pit may be a source of some of the contaminants appearing in the downdip borings.

At site M, the sludge is placed in the pond as a slurry and in some places has such low bearing capacity that it will not support the drill rig. At this site, the results of the randomization test indicate that sulfate, chloride and sodium levels are significantly increased in the groundwater under the disposal pond. This is as would be expected if typical sludge pond liquor were moving into the groundwater. Groundwater samples from borings

TABLE 19. CHEMICAL COMPOSITION OF GROUNDWATER FROM WELLS NEAR SITE I.

Local well number	1	3	4	5	6	7	8	10	Range
Conc. (mg/ℓ)									
SO_4	56	480	97	96	64	130	290	74	56-480
Cl	24	13	82	140	42	15	190	18	13-190
F	0.5	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2-0.5
CO_3	0	0	0	0	0	0	0	0	0
HCO_3	122	473	418	363	435	424	450	440	122-473
NO_3	0.00	0.00	2.70	0.40	1.30	0.00	0.60	0.00	0.00-2.70
SiO_2	7.6	17.0	16.0	16.0	20.0	19.0	17.0	19.0	7.6-20.0
Ca	40	250	120	140	100	120	220	120	40-250
Fe	0.10	6.30	1.50	14.000	0.30	1.30	3.60	6.90	0.10-14.00
K	3.0	3.9	2.9	2.4	3.0	2.6	7.5	1.4	1.4-7.5
Mg	10	52	38	40	35	36	49	35	10-52
Mn	0.18	1.60	0.90	1.20	0.00	0.50	2.70	0.21	0-2.70
Na	18	10	46	26	35	14	65	11	10-65

ND = Not determined.

under the disposal site contain concentrations of sulfate, manganese, boron and selenium that exceed the levels recommended for public water supply systems. Concentrations of sulfate, chloride, calcium and sodium in groundwater under the site are above the maximum concentrations found in published well water analyses in the same gravel aquifer (Table 20). Sulfate levels are up to 177% higher, chloride 32% higher, calcium 16% higher and sodium 47% higher.

At site M, the location of the control holes and the flow pattern in the aquifer allowed dilution to be observed in down gradient control borings 5 and 6. These two holes may be on the margin of the pollution plume. Control boring 7, however, has the highest levels of total organic carbon, calcium, magnesium and manganese observed in any groundwater sample from this site. Boring 7 may be showing the maximum effect of the plume from the disposal pond with possible added effects of pollution from coal storage pile drainage.

From the groundwater analyses of all three sites sampled, it can be concluded that FGC sludge (and ash) disposal degrades groundwater quality if contaminated water from the site is allowed to escape into the water table. At site K contaminants are found only in borings penetrating directly through FGC sludge or through a local, perched water table associated with the disposal pond. The lack of permeable geologic materials around the pond appears to be responsible for the high degree of pollutant containment that could be observed. At site L, the surrounding materials are permeable sands and gravels, but relatively dry sludge is being placed in a pit not in a settling pond and little water is maintained above the sludge and ash. Greatest contamination is observed in borings down the groundwater gradient rather than under the disposal pit. At site M, the settling/disposal pond is also situated on permeable sands and gravel. Degradation of groundwater quality was detected both beneath and down the groundwater gradient from the disposal pond.

CHEMICAL ANALYSIS OF DISTILLED WATER EXTRACTS

The goal of the distilled water extraction procedure was to determine the availability of chemical constituents to water contacting the soils. The content of this soil extract varies depending on the following:

a) the original components of the soil and their solubilities in distilled water,

b) the way in which these components have interacted with leachate from the FGC sludge/ash mixture,

c) the extent to which water-soluble and leachate-soluble components of the soil have been removed through solution,

d) the solubilities of materials that are precipitated, filtered or absorbed from the leachate, and

e) the amount and content of the interstitial water present in the samples.

TABLE 20. CHEMICAL COMPOSITION OF GROUNDWATER FROM WELLS NEAR SITE M

Local well number	1	16	15	14	Range
Conc. (mg/ℓ)					
SO_4	133	180	52	130	52-180
Cl	34	21	16	16	16-34
F	0.5	0.4	0.2	0.3	0.2-0.5
CO_3	ND	ND	ND	ND	
HCO_3	390	219	790	337	219-790
NO_3	1.1	0.1	0.2	0.2	0.1-1.1
SiO_2	20	16	30	18	16-30
Ca	105	70	190	85	70-190
Fe	3.30	0.22	3.80	0.59	0.22-3.80
K	5.4	6.1	9.1	5.7	5.4-9.1
Mg	34	20	45	23	20-45
Mn	1.9	0.30	5.60	0.44	0.30-5.60
Na	46	60	23	55	23-60

ND = Not determined.

Examination of pond liquor and elutriate from FGC sludges (Table 16) indicates that leachate from FGC disposal areas will be saturated with respect to calcium sulfate, will have a high pH, and will contain appreciable amounts of sodium, chloride, boron, cadmium, chromium, iron, lead, manganese and selenium. In passing through the soil/sediment, this solution will undergo ion exchange with clay minerals encountered, bring about increased solubilization of silica or aluminum, and cause some precipitation of metals dissolved in interstitial water but the major portion of material in solution in the leachate will remain in solution and will be carried into the groundwater. It is expected that attenuation by filtration, adsorption or ion exchange will reduce the pollution potential of the leachate only slightly.

Comparison of Distilled Water Extracts Beneath and Outside the Disposal Sites

The results of the chemical analyses of the distilled water extracts of the soil samples are given in Tables 21-26. The results of the randomization test are given in Table 27. At site K, significant differences in the composition of the distilled water extracts were observed only for nitrate and mercury. Nitrate showed a small increase in water extracts of sub-site soils. This may have been due to the presence of nitrates scrubbed from the flue gas. The small decrease in mercury observed in the distilled water extract from the sub-site soil may be related to the increased alkalinity (high pH) of the leachate from the sludge pond. Most metals have low solubility under moderately alkaline conditions.

At site L, the randomization test showed significant increases in sulfate, sodium and boron in distilled water extracts from soil directly beneath the disposal site as compared to soil samples taken at comparable depths outside the disposal site. These were the only significant contrasts noted at this site. High sodium and sulfate levels would be expected from a FGC sludge leachate because the interstitial water in the sludge commonly contains both of these constituents. Elevated levels of boron are usually associated with ash, not FGC sludge. Therefore it is likely that the boron is derived from ash co-disposed with the air cleaning sludge.

At site M, sulfate, boron, potassium, arsenic and selenium showed significantly increased levels in the distilled water extracts from under the disposal site as contrasted with the soil/sediment samples collected at similar elevations outside the disposal site. The latter four elements are associated with ash more often than with FGC sludges, therefore the increases detected in these elements can probably be related to the ash co-disposed with the FGC sludge. Significant decreases in nitrite, iron, magnesium and manganese were detected in the distilled water extracts from under the disposal site. The lower nitrite level was probably related to low levels of nitrite in the FGC/ash leachate and the lack of vegetation that releases nitrogen compounds in the disposal pit as compared to the surrounding area. The lower iron, magnesium and manganese levels were probably related to the higher pH that would lower the solubility of these metals under the disposal site.

In general very little contrast in concentration of distilled-water extractable materials was detected under the disposal sites. The most con-

TABLE 21. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE K

Boring and sample	1C1	1C2	1C3	1C4	2C1	2C2	2C3	2C4
Elevation (m)	261.23	260.42	258.30	256.32	260.01	258.04	257.17	255.07
Depth below sludge/soil interface (m)	0.23	1.14	3.26	5.24	-1.83	0.14	1.01	3.11
Ht. above water table (m)	-0.23	-1.14	-3.26	-5.24	5.00	3.17	2.16	0.06
Conc. (mg/ℓ)								
SO_4	42	24	8	20	1400	20	20	16
SO_3	1	<1	<1	<1	16	<1	<1	<1
Cl	<5	<5	<5	<5	10	<5	<5	<5
NO_3-N	0.11	ND	0.29	0.18	0.03	0.11	0.06	0.10
NO_2-N	0.02	ND	0.02	<0.01	<0.01	<0.01	<0.01	<0.01
CN	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	14	12	2	2	1	8	<1	<1
Ca	7.50	5.00	11.00	7.00	2.70	650.00	9.50	14.00
Fe	26.750	6.500	0.332	0.099	2.350	0.340	1.560	0.117
K	ND	ND	ND	ND	ND	ND	ND	ND
Mg	12.00	3.20	3.00	2.90	2.80	2.50	2.20	3.40
Mn	0.158	0.043	0.004	<0.002	0.362	0.019	0.009	<0.002
Na	23.00	12.00	8.50	12.00	4.90	5.10	7.90	6.20
As	ND	ND	ND	ND	ND	ND	ND	ND
B	0.12	0.05	0.04	0.08	<0.02	<0.02	0.94	<0.02
Be	0.0070	0.0040	<0.0005	<0.0005	0.0005	0.1330	<0.0005	<0.0005
Cd	0.0450	0.0005	0.0003	0.0003	<0.0003	<0.0003	<0.0003	0.0003
Cr	0.141	0.032	0.036	<0.003	<0.003	0.078	<0.003	<0.003
Cu	0.041	0.003	<0.003	<0.003	0.008	<0.003	<0.003	<0.003
Hg	<0.0002	<0.0002	<0.0002	0.0010	<0.0002	<0.0002	0.0007	<0.0002
Ni	0.106	0.030	0.073	0.034	<0.005	1.560	0.038	0.075
Pb	0.010	0.002	<0.002	<0.002	0.002	<0.002	<0.002	<0.002
Se	ND	ND	ND	ND	ND	ND	ND	ND
Zn	0.231	0.080	0.043	0.079	0.108	0.246	0.159	0.079

ND = Not determined.

TABLE 22. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE K

Boring and sample	3C5	5C1	5C2	6C1	6C2	6C3	7C1	7C2	7C3	7C4
Elevation (m)	251.45	257.30	256.38	262.42	261.51	257.89	262.42	261.20	259.40	257.84
Ht. above water table (m)	7.65	(dry)	(dry)	2.36	1.45	-2.17	(dry)	(dry)	(dry)	(dry)
Position in groundwater gradient	Downdip	Downdip	Downdip	Updip	Updip	Updip	Updip	Updip	Updip	Updip
Conc. (mg/ℓ)										
SO_4	120	180	46	68	18	40	28	24	16	16
SO_3	1	1	<1	<1	<1	1	<1	1	<1	<1
Cl	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
NO_3-N	0.06	0.05	0.02	<0.01	<0.01	0.02	0.01	0.03	0.04	0.04
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	<0.01	0.01
CN^2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	38	42	14	2	10	8	7	11	5	16
Ca	8.00	13.00	9.00	6.50	6.00	2.50	7.00	6.00	8.00	4.50
Fe	35.000	180.000	34.500	0.690	2.500	1.210	0.623	10.500	1.130	8.000
K	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mg	8.00	34.00	16.00	3.50	3.10	2.80	4.20	3.20	3.20	4.40
Mn	0.402	0.577	0.227	<0.002	0.018	0.011	0.010	0.176	0.004	0.074
Na	4.30	25.00	25.00	36.00	54.00	14.00	16.00	9.00	15.00	11.00
As	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
B	0.06	0.24	0.10	0.04	0.05	0.06	0.10	<0.02	0.046	0.043
Be	0.0060	0.0180	0.0080	<0.0005	0.0010	<0.0005	<0.0005	0.0010	<0.0005	0.0020
Cd	<0.0003	0.0011	0.0011	0.0006	<0.0003	0.0007	0.0005	0.0006	0.0004	0.0003
Cr	0.081	0.401	0.138	<0.003	0.004	<0.003	<0.003	0.099	<0.003	0.003
Cu	0.025	0.110	0.030	<0.003	<0.003	<0.003	<0.003	0.055	<0.003	0.003
Hg	0.0004	0.0015	<0.0002	<0.0002	<0.0002	<0.0002	0.0012	0.0004	<0.0002	<0.0002
Ni	0.106	0.283	0.134	0.035	0.035	<0.005	<0.005	0.067	<0.005	0.006
Pb	0.012	0.090	0.026	0.002	<0.002	0.087	0.006	0.016	<0.002	0.012
Se	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Zn	0.317	0.764	0.326	0.066	0.033	0.050	0.058	0.135	0.102	0.130

ND = Not determined.

TABLE 23. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE L

Boring and sample	1C1	1C2	1C3	1C4	2C1	2C2	2C3	2C4
Elevation (m)	132.02	130.48	129.56	127.48	130.25	123.39	122.91	121.98
Depth below sludge/soil interface (m)	-1.45	0.09	1.01	3.10	-7.24	-0.38	0.10	1.03
Ht. above water table (m)	10.75	9.21	8.29	6.21	8.49	1.63	1.15	0.22
Conc. (mg/ℓ)								
SO_4	1721	226	46	<8	316	496	146	66
SO_3	<1	<1	<1	<1	<1	<1	<1	<1
Cl	<5	<5	15	<5	<5	<5	<5	<5
NO_3-N	<0.01	0.21	0.04	0.24	0.50	0.58	0.02	0.34
NO_2-N	0.01	<0.01	<0.01	<0.01	0.01	0.02	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	6	4	4	<1	<1	<1	<1	16
Ca	478.30	24.70	17.60	12.00	149.30	254.30	13.30	20.30
Fe	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
K	ND	ND	ND	ND	ND	ND	ND	ND
Mg	0.940	11.600	7.300	2.400	1.000	0.400	0.250	1.600
Mn	<0.002	<0.002	4.720	<0.002	<0.002	<0.002	0.038	<0.002
Na	12.20	5.40	1.40	0.59	5.80	3.10	21.20	18.60
As	0.058	<0.005	<0.005	<0.005	0.025	0.025	<0.005	<0.005
B	8.10	2.19	0.15	<0.02	11.25	3.95	0.51	0.54
Be	<0.0005	<0.0005	<0.0005	<0.0005	0.0100	0.0100	<0.0005	<0.0005
Cd	<0.0003	0.0220	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Cr	0.003	<0.003	<0.003	<0.003	0.035	0.036	<0.003	<0.003
Cu	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Hg	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Ni	<0.005	<0.005	0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Pb	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Se	0.058	<0.005	<0.005	<0.005	0.035	0.041	<0.005	<0.005
Zn	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014

ND = Not determined.

TABLE 24. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE L

Boring and sample	3C5	4C1	4C2	4C3	4C4	4C5	5C1	5C2	5C3
Elevation (m)	121.30	132.97	128.70	124.60	123.55	121.42	130.60	129.69	127.59
Ht. above water table (m)	-0.41	10.93	6.66	2.56	1.51	-0.62	9.22	8.31	6.21
Position in groundwater gradient	Updip	Updip	Updip	Updip	Updip	Updip	Downdip	Downdip	Downdip
Conc. (mg/L)									
SO_4	8	14	<8	<8	<8	<8	21	56	14
SO_3	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cl	35	<5	15	<5	100	25	<5	<5	<5
NO_3-N	0.50	0.11	0.01	0.09	0.02	0.19	0.67	1.14	1.60
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
TOC	2	<1	17	18	<1	10	<1	<1	<1
Ca	38.30	4.30	15.10	8.50	69.10	33.50	16.10	27.50	13.80
Fe	<0.003	<0.003	<0.003	0.290	<0.003	<0.003	0.100	<0.003	<0.003
K	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mg	6.60	3.10	6.00	2.20	7.90	6.20	6.50	11.50	5.00
Mn	0.020	0.003	<0.002	0.016	0.044	0.120	<0.002	<0.002	<0.002
Na	1.00	0.97	0.51	0.38	0.38	1.10	1.40	4.10	1.20
As	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
B	0.04	<0.02	<0.02	<0.02	<0.02	<0.02	0.10	0.30	0.17
Be	<0.0005	<0.0005	0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cd	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Cr	0.011	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	0.004	<0.003
Cu	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Hg	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Ni	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Pb	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Se	0.008	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Zn	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014

(continued)

TABLE 24 (CONTINUED)

Boring and sample	5C4	5C5	5C6	6C5	7C1	7C2	7C3	7C4	7C5
Elevation (m)	125.45	123.44	121.30	121.64	133.22	128.89	124.98	123.94	121.90
Ht. above water table (m)	4.07	2.06	-0.08	0.33	11.37	7.04	3.13	2.09	0.05
Position in groundwater gradient	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip
Conc. (mg/ℓ)									
SO_4	15	<8	<8	11	<8	<8	<8	<8	<8
SO_3	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cl	<5	15	10	<5	25	<5	<5	<5	<5
NO_3-N	2.90	0.16	0.13	0.19	0.07	<0.01	0.01	0.04	0.12
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	8	6	6	<1	2	5	<1	<1	3
Ca	18.50	19.10	14.50	12.10	11.50	10.30	8.80	9.50	11.80
Fe	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
K	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mg	5.60	3.90	3.60	2.60	7.90	3.60	2.10	2.40	2.00
Mn	<0.002	0.003	<0.002	<0.002	0.107	<0.002	<0.002	0.002	0.002
Na	1.20	0.34	0.42	0.47	0.55	0.38	0.30	0.51	1.40
As	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
B	0.18	<0.02	<0.02	0.10	<0.02	<0.02	<0.02	<0.02	0.30
Be	<0.0005	<0.0005	0.0100	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cd	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	0.0007	<0.0003	<0.0003	<0.0003
Cr	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Cu	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Hg	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Ni	<0.005	<0.005	<0.005	<0.005	0.020	0.009	<0.005	<0.005	<0.005
Pb	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Se	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Zn	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014

ND = Not determined.

TABLE 25. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE M

Boring and sample	1C1	1C2	1C3	1C4	4C1	4C2	4C3	4C4	4C5
Elevation (m)	222.77	220.81	218.96	217.73	221.98	221.07	218.93	217.41	216.65
Depth below sludge/soil interface (m)	-1.89	0.07	1.92	3.15	0.09	1.00	3.14	4.66	5.42
Ht. above water table (m)	5.96	4.00	2.15	0.92	5.03	4.12	1.98	0.46	-0.30
Conc. (mg/ℓ)									
SO_4	76	<8	28	39	150	11	<8	41	39
SO_3	190	<1	<1	<1	<1	<1	<1	<1	<1
Cl	10	<5	<5	<5	10	<5	<5	<5	<5
NO_3-N	<0.01	<0.01	0.12	0.09	0.10	0.02	0.04	0.02	0.01
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	5	3	2	2	11	18	2	<1	9
Ca	56.20	5.10	10.10	10.50	73.20	17.80	6.20	14.10	13.70
Fe	<0.003	<0.003	0.320	<0.003	<0.003	0.470	0.320	0.530	0.380
K	35.00	14.80	3.00	1.30	18.20	9.70	1.80	3.70	3.10
Mg	<0.03	<0.03	1.10	2.00	0.22	0.76	0.52	1.40	0.67
Mn	<0.002	0.002	0.007	0.002	0.003	0.030	0.010	0.011	0.006
Na	20.30	8.20	3.90	4.30	24.50	16.00	2.60	6.10	4.80
As	0.011	0.031	0.007	<0.005	0.018	<0.005	<0.005	<0.005	<0.005
B	0.04	0.13	0.05	0.04	2.15	1.01	0.11	0.97	0.36
Be	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cd	0.0019	<0.0003	<0.0003	<0.0003	0.0005	0.0005	<0.0003	<0.0003	<0.0003
Cr	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Cu	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Hg	<0.0002	0.0005	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Ni	0.024	<0.005	<0.005	<0.005	<0.005	0.009	<0.005	<0.005	<0.005
Pb	<0.002	<0.002	0.009	0.005	<0.002	0.004	0.007	<0.002	0.002
Se	0.014	0.009	0.005	<0.005	0.151	0.005	<0.005	<0.005	<0.005
Zn	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014

ND = Not determined.

TABLE 26. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE M

Boring and sample	2C1	2C2	2C3	2C4	3C1	3C2	3C3
Elevation (m)	221.78	220.87	218.72	217.97	221.70	220.79	218.64
Ht. above water table (m)	3.96	3.05	0.90	0.15	4.60	3.69	1.54
Position in groundwater gradient	Updip	Updip	Updip	Updip	Updip	Updip	Updip
Conc. (mg/ℓ)							
SO_4	12	<8	16	<8	16	21	8
SO_3	<1	<1	<1	<1	<1	<1	<1
Cl	<5	<5	<5	<5	<5	<5	<5
NO_3-N	0.92	0.16	0.30	0.24	ND	0.01	0.07
NO_2-N	0.02	<0.01	<0.01	<0.01	0.02	0.04	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	7	3	5	2	6	4	4
Ca	12.80	11.60	19.00	17.10	30.10	17.10	19.90
Fe	0.620	0.410	1.100	<0.003	0.620	3.000	<0.003
K	0.77	0.53	1.80	1.70	1.60	0.95	5.00
Mg	3.00	5.10	4.30	3.70	4.70	3.60	7.00
Mn	0.007	0.053	0.018	0.002	0.014	0.039	0.012
Na	0.83	0.96	1.20	1.20	0.83	0.74	4.50
As	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
B	0.03	<0.02	<0.02	<0.02	0.04	0.03	0.05
Be	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cd	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003	<0.0003
Cr	<0.003	<0.003	<0.003	<0.003	0.003	<0.003	<0.003
Cu	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Hg	<0.0002	0.0005	<0.0002	0.0003	0.0004	<0.0002	<0.0002
Ni	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Pb	0.003	0.006	0.002	<0.002	0.002	0.005	<0.002
Se	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Zn	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014	<0.014

(continued)

TABLE 26 (CONTINUED)

Boring and sample	3C4	5C4	6C4	7C1	7C2	7C3	7C4
Elevation (m)	217.89	217.17	216.14	221.09	220.18	218.05	216.52
Ht. above water table (m)	0.79	0.03	-0.03	4.84	3.93	1.80	0.27
Position in groundwater gradient	Updip	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip
Conc. (mg/ℓ)							
SO_4	8	<8	<8	45	37	45	35
SO_3	<1	<1	<1	<1	<1	<1	<1
Cl^3	<5	<5	<5	<5	<5	<5	<5
NO_3-N	0.12	0.04	0.01	2.72	1.02	0.62	0.01
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	0.13	<0.01
CN^2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	3	<1	<1	9	4	8	<1
Ca	12.70	7.20	6.20	31.70	33.50	38.50	20.80
Fe	0.290	0.650	0.710	0.440	0.230	0.120	<0.003
K	1.80	0.84	0.95	5.10	3.00	6.00	3.50
Mg	4.00	2.40	2.80	3.80	6.70	9.70	7.10
Mn	0.003	0.007	0.015	0.006	0.006	0.007	0.002
Na	1.10	0.61	1.00	1.60	2.10	8.30	6.70
As	<0.005	<0.005	<0.005	0.010	<0.005	<0.005	<0.005
B	0.02	<0.02	<0.02	0.07	0.05	0.03	0.03
Be	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cd	<0.0003	<0.0003	<0.0003	0.0007	<0.0003	<0.0003	<0.0003
Cr	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Cu	<0.003	<0.003	<0.003	<0.003	<0.003	0.434	<0.003
Hg	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Ni	<0.005	<0.005	<0.005	<0.002	<0.005	<0.005	<0.005
Pb	0.002	0.002	0.002	<0.002	<0.002	0.010	<0.002
Se	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Zn	<0.014	<0.014	<0.014	<0.014	<0.014	0.247	<0.014

ND = Not determined.

TABLE 27. RESULTS OF RANDOMIZATION TEST ON DISTILLED WATER EXTRACTS OF SOIL SAMPLES DIRECTLY UNDER THE FGC DISPOSAL SITES AND AT COMPARABLE DEPTHS OUTSIDE THE SITES

Parameters	Site K	Site L	Site M
SO_4	NS	S(increase)	NS
SO_3	NS	BDL	BDL
Cl	BDL	BDL	BDL
NO_3-N	S(increase)*	NS	NS
NO_2-N	NS	BDL	S(decrease)
CN	BDL	BDL	BDL
TOC	NS	NS	NS
Ca	NS	NS	NS
Fe	NS	BDL	S(decrease)
K	ND	ND	S(increase)
Mg	NS	NS	S(decrease)
Mn	NS	NS	S(decrease)
Na	NS	S(increase)	S(increase)
As	ND	ND	S(increase)
B	NS	S(increase)	S(increase)
Be	NS	BDL	BDL
Cd	NS	BDL	NS
Cr	NS	BDL	BDL
Cu	NS	BDL	BDL
Hg	S(decrease)	BDL	NS
Ni	NS	BDL	BDL
Pb	NS	BDL	NS
Se	ND	BDL	S(increase)
Zn	NS	BDL	BDL

NS = Not significant at 80% confidence level.

S = Significant at 80% confidence level.

BDL = Below detection limits.

ND = Not determined.

* Refers to increase or decrease of constituent under disposal site relative to outside.

sistent changes found were increased levels of sodium and boron. Elevated concentrations of sulfate were detected at site L. The immobilization of some metals, probably due to high pH levels, was detected at sites K and M.

Vertical Variations of Concentrations in Distilled Water Extracts of Soil Samples

For those elements that did show a significant difference between control (outside disposal site) samples and experimental (inside disposal site) samples, a test was made for a significant relationship between the available concentration of a particular constituent and sample elevation. As suggested by the model (Figure 1), those materials present in the sludge liquor should show a positive correlation with elevation in experimental borings (these below the disposal area). A significant negative correlation would be predicted by the model for those soil constituents that are being dissolved by the sludge liquor and moved down out of the soil and into the groundwater. In control borings the distribution of available soil constituents depends on weathering processes and the concentration and solubility of the particular material, and could therefore have a significant positive or negative correlation with elevation or no significant correlation at all.

A non-parametric test of association, the Spearman rank correlation coefficient, was used to assess the strength of association between the concentration of a particular soil constituent and sample elevation. This technique is suited especially for use with small sample numbers where the statistical distribution is not known. In several cases, the small number of samples having detectable quantities of a particular constituent made it impossible to judge the significance of the correlation coefficients obtained. The results of the statistical tests are given in Tables 28-30. Plots of concentration versus sample elevation for all constituents in experimental borings that showed statistically significant relationships with depth are presented in Figures 7-11. Plots of significant relationships in control borings are included for contrast. At site K, no soil/sediment constituents, as tested above, showed any significant relationship with sample elevation. This was not unexpected, as only nitrate and mercury showed any contrast under and outside the disposal pond. The pond itself is underlain by impervious Pennsylvanian shales and limestones which decreases the likelihood of vertical migration of sludge constituents.

Site L (especially boring 1) comes closest to giving results predicted by the model for pollutant migration. The pattern of leachable constituents observed under the disposal pit (a significant positive correlation with elevation) indicates that the sludge/ash in the pit is contributing boron, sodium, and sulfate to the soil below the pit in a water-extractable form. The sands and gravels below the pit in this hole have low cation exchange capacities and most of the material in these samples is probably reflecting the concentration of these constituents in the infiltrating water.

At site M, many soil constituents showed significant contrasts beneath and outside the disposal pond; but, only potassium and selenium (in boring 1) showed a significant correlation of concentration in distilled water extracts versus sample elevation under the site. The most striking aspect of this data

TABLE 28. CORRELATION OF CHEMICAL ANALYSES OF DISTILLED WATER EXTRACTS OF SOILS WITH SAMPLE ELEVATION AT SITE K

Boring	1	2	6	7
NO_3-N	NS(0.80)*	NS(-0.40)	NS(-0.50)*	NS(-0.80)
Hg	NS(-0.20)	NS(0.40)	**	SP(1.00)

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = No significant correlation.

* = Significance level reduced to 83% because of small sample size for this constituent in this boring.

** = Too few samples above detection limits.

Number in parentheses is the calculated value of r_S, the Spearman rank correlation coefficient.

TABLE 29. CORRELATION OF CHEMICAL ANALYSES OF DISTILLED WATER EXTRACTS OF SOILS WITH SAMPLE ELEVATION AT SITE L

Boring	1	2	4	5	7
SO_4	SP(1.00)	NS(0.80)	**	SP(0.88)	**
Na	SP(1.00)	NS(-0.60)	NS(0.00)	SP(0.88)	NS(-0.30)
B	SP(1.00)	NS(0.80)	**	NS(0.60)	**

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = No significant correlation.

** = Too few samples above detection limits.

Number in parentheses is the calculated value of r_s, Spearman rank correlation coefficient.

TABLE 30. CORRELATION OF CHEMICAL ANALYSES OF DISTILLED WATER EXTRACTS OF SOILS WITH SAMPLE ELEVATION AT SITE M

Boring	1	4	2	3	7
NO_2-N	**	**	**	NS(0.80)	**
Fe	**	NS(-0.50)	NS(0.40)	NS(0.60)	SP(1.00)
K	SP(1.00)	NS(0.70)	NS(-0.60)	NS(-0.60)	NS(0.00)
Mg	NS(-0.80)	NS(-0.50)	NS(-0.20)	NS(0.00)	NS(-0.80)
Mn	NS(-0.40)	NS(-0.10)	NS(0.40)	NS(0.80)	NS(0.40)
Na	NS(0.80)	NS(0.70)	NS(-0.80)	NS(-0.60)	NS(-0.80)
As	NS(0.80)	**	**	**	**
B	NS(0.40)	NS(0.70)	**	NS(0.40)	SP(1.00)
Se	SP(1.00)	**	**	**	**

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = No significant correlation.

** = Too few samples above detection limits.

Number in parentheses is the calculated value of r_s, the Spearman rank correlation coefficient.

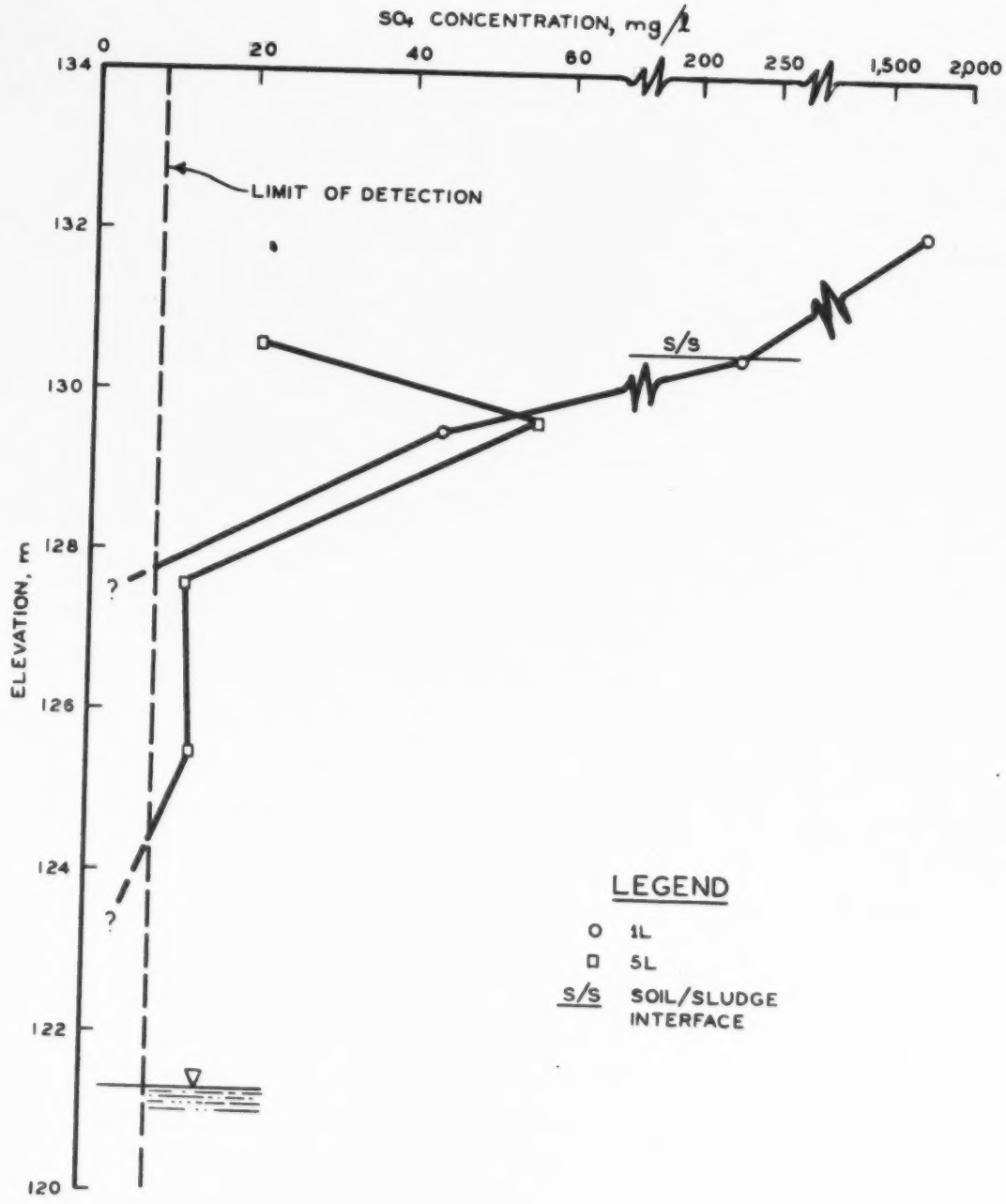

Figure 7. Variation of sulfate concentration in distilled water extracts of soil/sediment samples with elevation in borings 1 and 5 at site L.

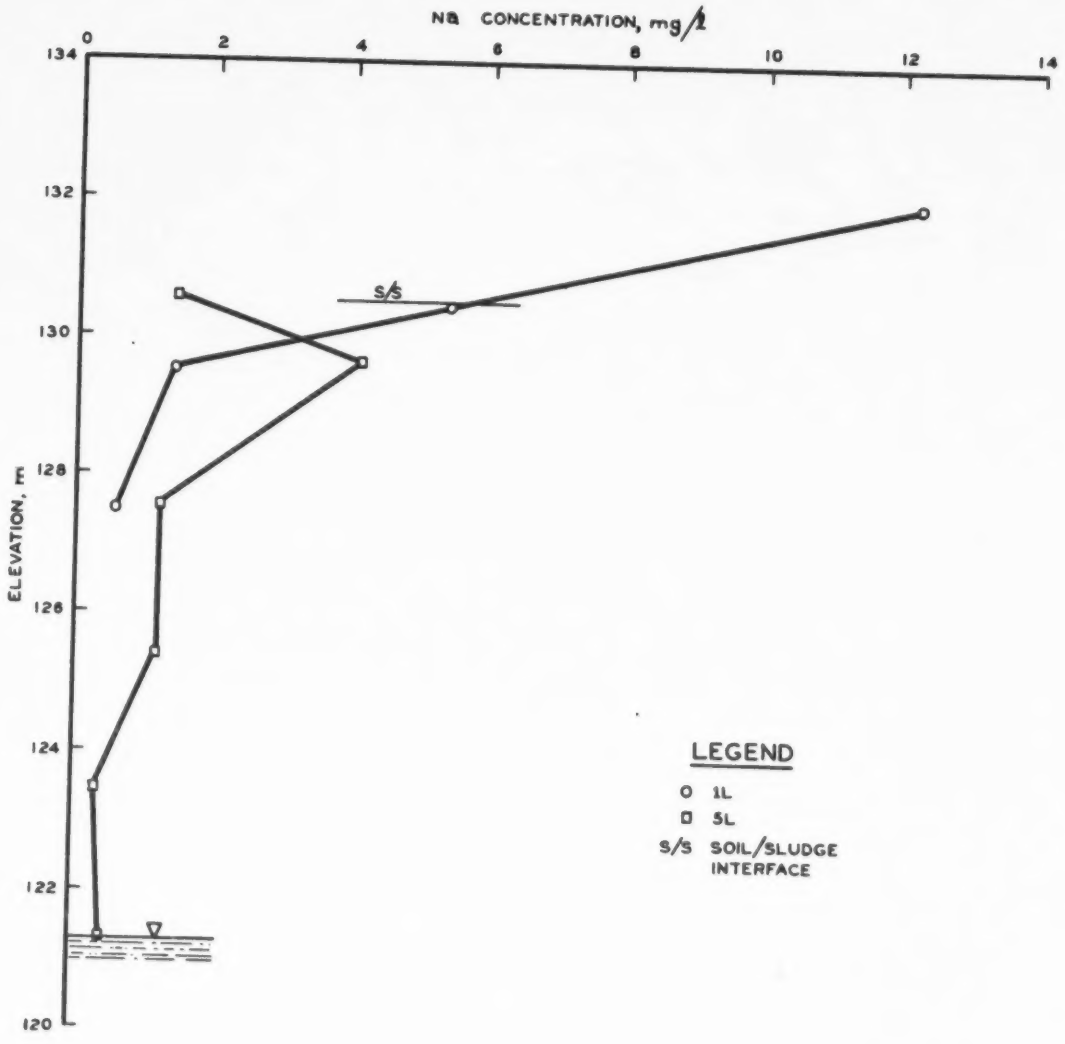

Figure 8. Variation of sodium concentration in distilled water extracts of soil/sediment samples with elevation in borings 1 and 5 at site L.

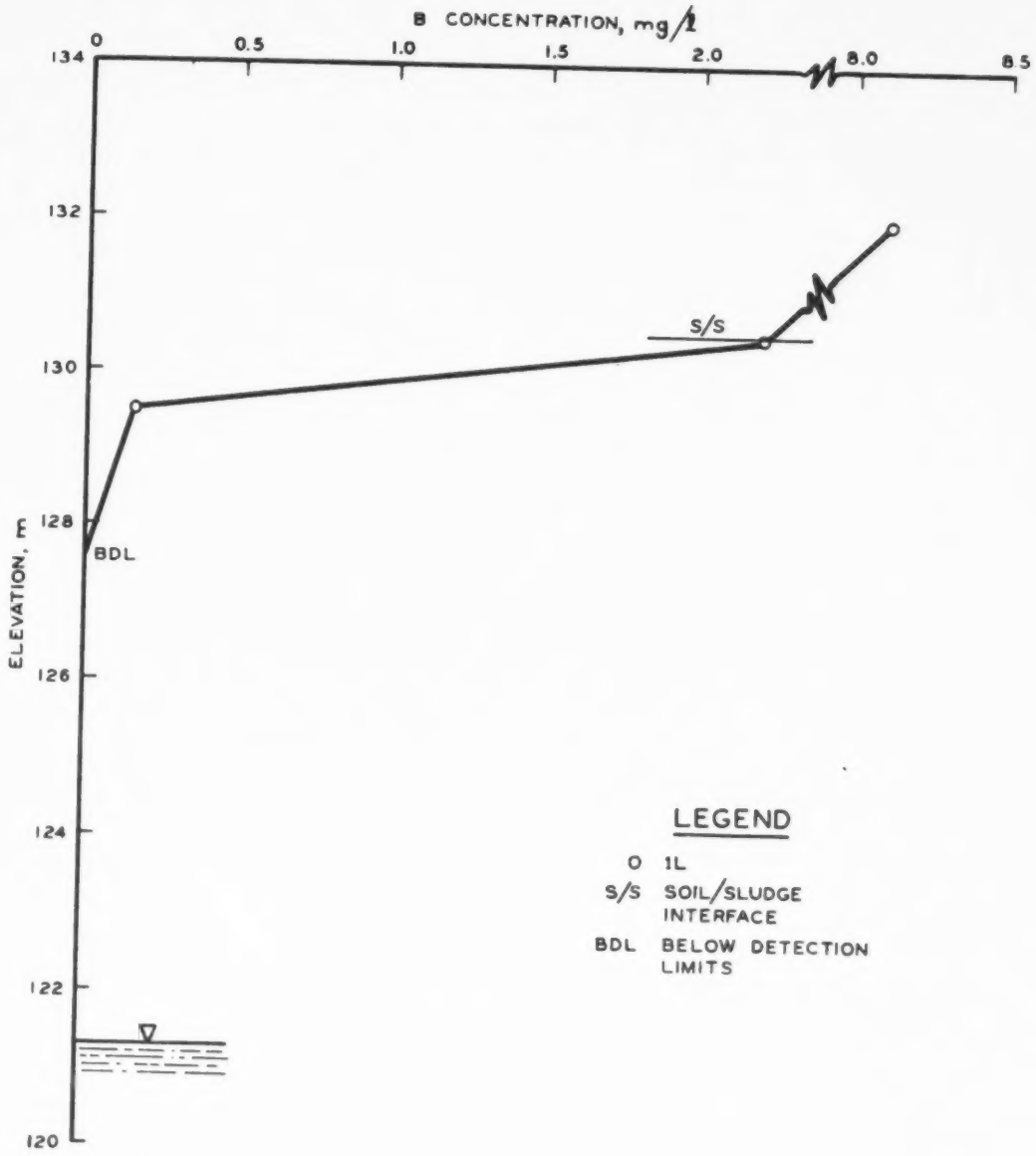

Figure 9. Variation of boron concentration in distilled water extracts of soil/sediment samples with elevation in boring 1 at site L.

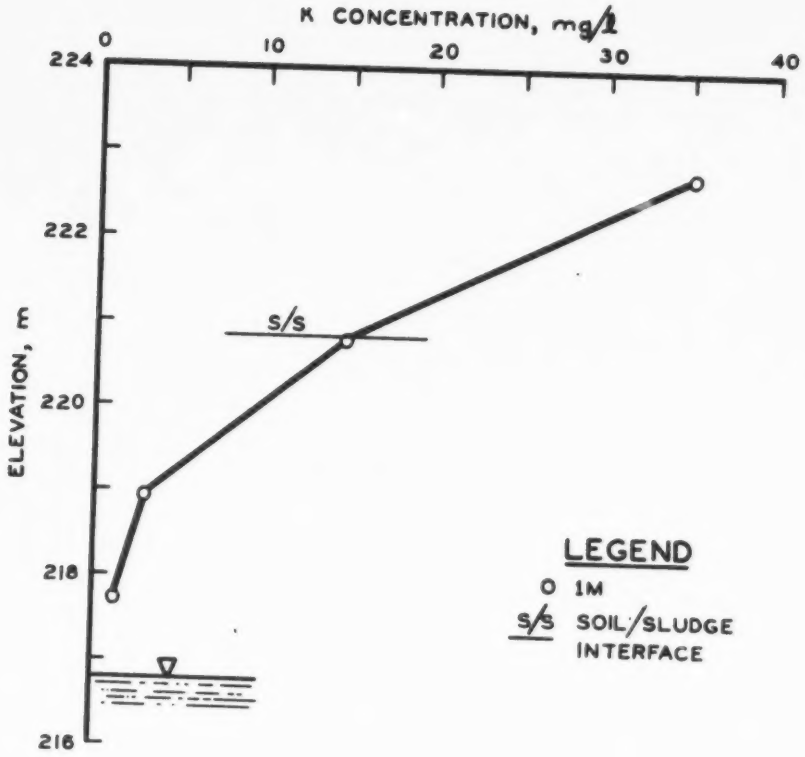

Figure 10. Variation of potassium concentration in distilled water extracts of soil/sediment samples with elevation in boring 1 at site M.

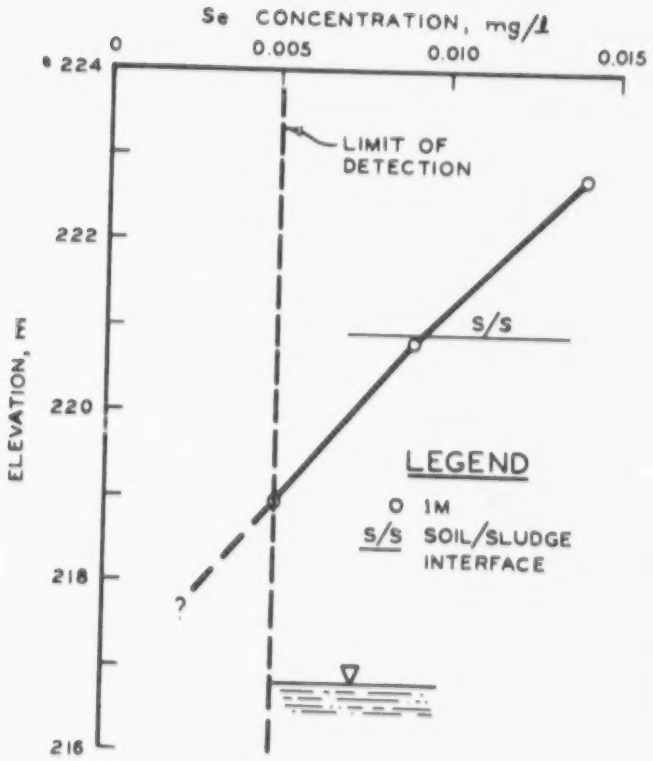

Figure 11. Variation of selenium concentration in distilled water extracts of soil/sediment samples with elevation in boring 1 at site M.

set is that most of the soil constituents were so uniformly distributed through the soil/sediment column. Possible explanations of this uniformity are that the interstitial water is the major source of the materials measured and that this water moves unchanged through the soil/sediment column, or that the removal capacity of the soil has been exhausted.

As expected, the soils beneath the disposal sites did not hold any appreciable quantities of water-extractable materials that could be related to the pollutants from the FGC sludge/ash. The high levels of contamination observed in the groundwater indicate that pollutants have passed through the soil, but the low levels of contaminants found in the distilled water extracts indicate the polluting material does not remain in the soil in a water soluble condition.

Horizontal Variation in Distilled Water Extracts of Soil/Sediment Samples Below the Water Table

Analyses of distilled water extracts of soil/sediment samples collected below the water table were examined in order to determine if sludge-derived materials were accumulating below this horizon in a water-extractable form. Plots of cross-sections through the site versus concentration are shown in Figures 12-15. The model of groundwater movement assumes all significant lateral migration of pollutants occurs below the water table. Two factors should effect the concentration of contaminants in distilled water extracts; the concentration of sludge-derived materials in infiltrating water and the character of the soil/sediment.

At site K, the highest values for all constituents measured were found under the disposal pond or downdip from the pond as predicted from the model situation. Sulfite, nitrate, nitrite, cyanide, calcium, magnesium, sodium, boron, beryllium, cadmium, chromium, copper, and lead were found in their maximum amounts in water extracts from directly under the disposal pond. Sulfate, total organic carbon, iron, manganese, mercury, nickel and zinc were found in their maximum concentrations down gradient from the disposal site. With the exception of boring 1, the level of contamination in the groundwater is not reflected by the level of constituents in the distilled water extract from soils. The low correlation with groundwater chemistry may reflect the strong influence of the original composition of the material that was extracted.

At site L, maximum concentrations in distilled water extracts were observed in borings under the disposal pit for sulfate, total organic carbon, sodium and boron. Maximum concentrations for chloride, nitrite, calcium, magnesium, manganese, chromium and selenium were found in upgradient borings. Maximum concentrations for cyanide and beryllium were found in down gradient borings. These results agree with the groundwater analyses in that elevated sodium and boron levels were noted under the disposal pit. For other constituents there seems to be no consistent pattern and all were found in low concentrations.

At site M, maxima for sulfate, total organic carbon, boron and lead were found under the disposal area. Maxima for nitrate and mercury were found in upgradient borings. Maximum levels for calcium, iron, potassium, magnesium, manganese and sodium occurred in the down gradient borings. At both sites M and L where the substrate is sand and gravel many consistuents were below

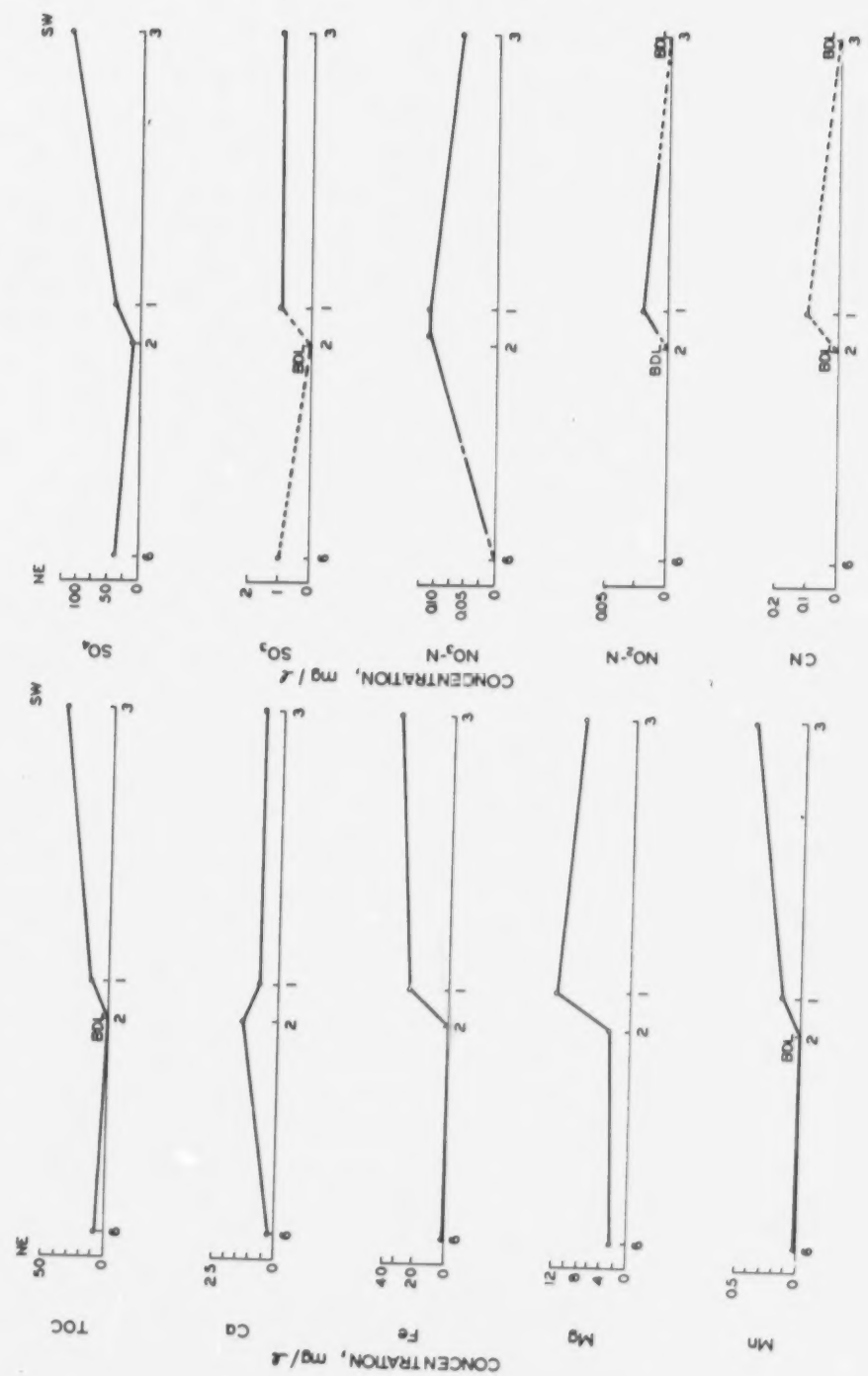

Figure 12. Horizontal variation in chemical composition of distilled water extracts at site K. BDL indicates below detection limits.

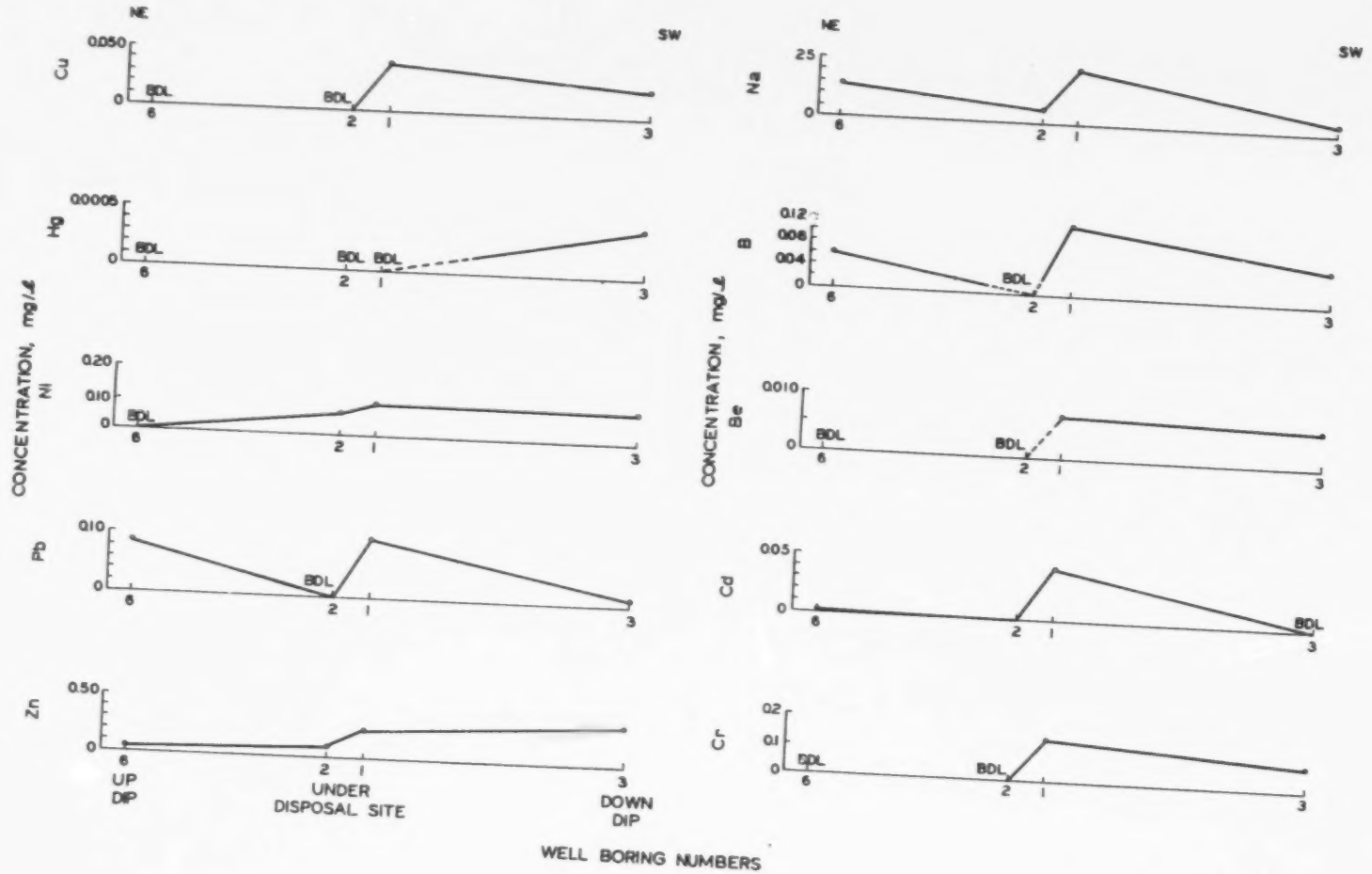

Figure 13. Horizontal variation in chemical composition of distilled water extracts at site K, continued. BDL indicates below detection limits.

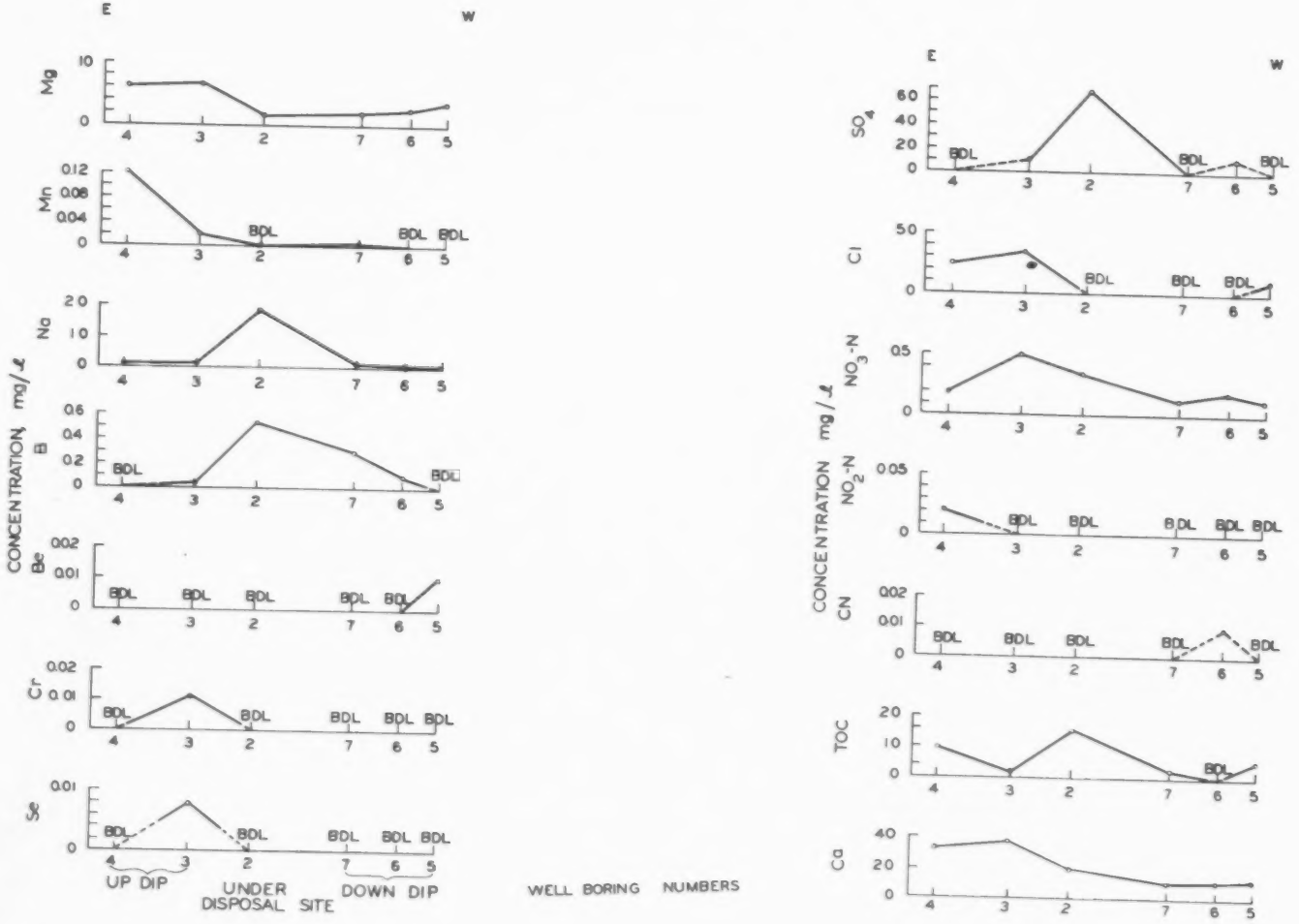

Figure 14. Horizontal variation in chemical composition of distilled water extracts at site L. BDL indicates below detection limits.

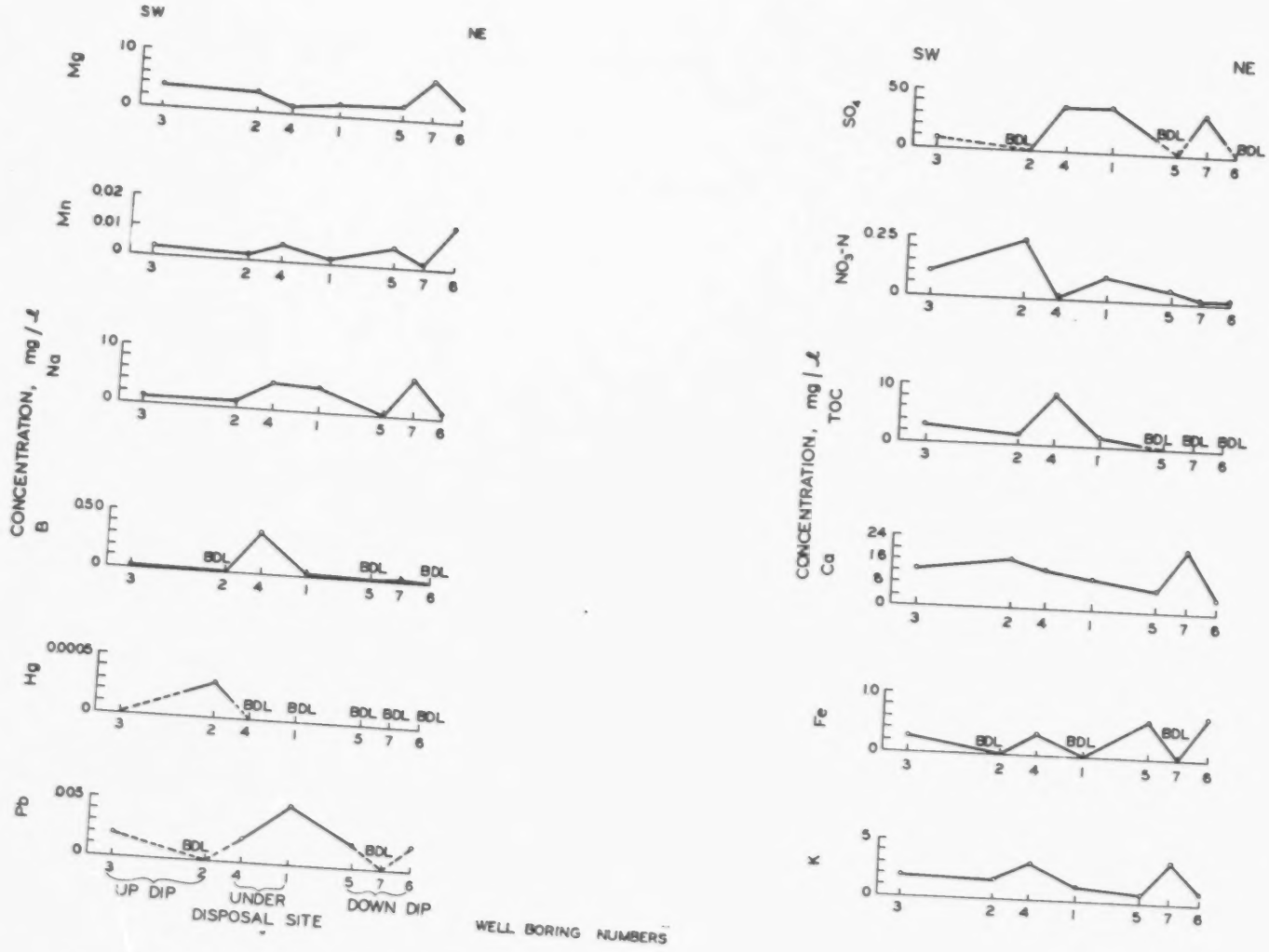

Figure 15. Horizontal variation in chemical composition of distilled water extracts at site M. BDL indicates below detection limits.

detection limits in all borings. In this situation where the underlying material is relatively uniform, the highest levels of sulfate, total organic carbon and boron are consistently associated with borings under the disposal area.

The use of analytical data from distilled water extracts to indicate the presence of loosely bound pollutant materials is limited because of the large differences produced by the changing nature of the geologic materials underneath the disposal areas, the background levels of exchangeable constituents that are likely to be present under an industrial area, and the limited capacity of many materials (expecially sand and gravel) to exchange or absorb incoming materials. Several major constituents (sulfate, sodium and boron) associated with FGC pond liquors did show a consistent distribution with maxima occurring under or down the groundwater gradient from the disposal areas.

CHEMICAL ANALYSES OF NITRIC ACID DIGESTS

The goal of the nitric acid digestion procedure was to determine the total amount of material that could be removed from the soil by rigorous treatment with a strong, oxidizing acid. This digest brings into solution all materials that are not tightly bound in a silicate lattice. Contaminants leached from the FGC disposal area and deposited in the soil should be released in the nitric acid digest. The evidence that attenuation is occurring would be the higher concentration of the attenuated materials under the disposal site as compared to similar samples outside the site and decreasing concentration in nitric acid digests of samples taken at decreasing elevations (increasing depths) below the disposal site. Evidence that mobilization of material from soil under the site is occurring would be the lower concentrations of material under the disposal site as compared to similar samples outside the site. In this case, concentrations of mobilized constituents would increase with decreasing elevations (increasing depth) below the disposal site. The absence of any significant difference between the concentrations of constituents in the nitric acid digest from the soils would indicate either no leachate is passing through the soil, or leachate passing through the soil is not interacting with the soil. Analyses of groundwater obtained from borings under and down the groundwater gradient from the disposal sites can indicate if sludge-derived constituents get through the soil into the groundwater.

Published analyses of pond liquor or elutriates (Table 16) indicate any leachate escaping from the disposal areas is saturated with calcium and sulfate, and is high in sodium and chloride. Common pH's are between 8 and 10. Leachate with a composition similar to pond liquor would be expected to pass through the soil with little interaction except possibly the displacement of exchangeable cations with calcium and loss of boron and potassium into clays in the soil. Any calcium, boron and potassium fixed in the soil should be brought into solution by the nitric acid digestion procedure.

Comparison of Nitric Acid Digests Beneath and Outside the Disposal Area

The chemical analyses for all the nitric acid digests are given in Tables 31-36. The results of the randomization test on nitric acid digests of soil

TABLE 31. ANALYSIS OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE K

Boring and sample	1C1	1C2	1C3	1C4	2C1	2C2	2C3	2C4
Elevation (m)	261.33	260.42	258.30	236.32	260.01	258.04	257.17	255.07
Depth below sludge/soil interface (m)	0.23	1.14	3.26	5.24	-1.83	0.14	1.01	3.11
Ht. above water table (m)	-0.23	-1.14	-3.26	-5.24	5.00	3.17	2.16	0.06
Conc. (mg/kg dry wt.)								
Ca	3416.96	4607.68	12240.04	31579.70	299450.35	2138.04	3458.55	14404.11
Fe	41649.47	83009.96	57120.17	25078.00	14518.80	30543.44	45595.02	51582.27
K	ND	ND	ND	ND	ND	ND	ND	ND
Mg	4334.94	11474.38	9384.03	7244.75	4083.41	2660.24	4781.92	8515.94
Mn	60.52	89.64	63.97	27.86	32.67	40.69	57.83	44.96
Na	86.70	699.22	261.12	380.81	204.17	128.09	211.29	107.06
As	ND	ND	ND	ND	ND	ND	ND	ND
B	ND	ND	ND	ND	ND	ND	ND	ND
Be	3.13	3.80	2.57	3.66	4.72	1.99	3.14	2.71
Cd	5.10	0.70	0.03	0.03	28.92	0.04	0.51	0.08
Cr	24.14	37.29	23.66	23.68	19.74	19.41	27.36	23.16
Cu	13.16	20.80	57.28	7.52	19.51	9.85	15.35	30.37
Hg	ND	ND	ND	ND	ND	ND	ND	ND
Ni	41.14	78.17	56.06	60.65	79.17	23.65	44.04	64.72
Pb	15.64	10.22	2.86	14.86	86.21	13.79	17.79	5.06
Se	ND	ND	ND	ND	ND	ND	ND	ND
Zn	39.61	85.88	57.28	24.24	969.81	34.88	56.05	57.03

ND = Not determined.

TABLE 32. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE K

Boring and sample	3C5	5C1	6C1	6C2	6C3	7C1	7C2	7C3	7C4
Elevation (m)	251.45	257.30	262.42	261.51	257.89	262.42	261.20	259.40	257.84
Ht. above water table (m)	-7.65	(dry)	2.36	1.45	-2.17	(dry)	(dry)	(dry)	(dry)
Position in groundwater gradient	Downdip	Downdip	Updip	Updip	Updip	Updip	Updip	Updip	Updip
Conc. (mg/ℓ)									
Ca	2568.73	2386.07	2527.65	14934.53	30.76	2918.62	1804.83	62724.06	56444.98
Fe	28966.50	56749.82	53564.75	42750.09	487.26	44530.42	56499.06	38116.93	22003.98
K	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mg	2732.69	3408.67	5593.11	7560.61	80.90	4560.34	3040.75	13220.30	11958.68
Mn	64.93	59.70	93.58	29.12	0.53	90.99	100.05	40.14	47.26
Na	98.38	690.95	516.29	774.73	2.73	386.29	196.18	299.15	344.41
As	ND	ND	ND	ND	ND	ND	ND	ND	ND
B	ND	ND	ND	ND	ND	ND	ND	ND	ND
Be	2.14	2.51	2.20	3.96	0.02	2.37	1.78	3.66	3.46
Cd	0.13	0.10	0.32	0.04	ND	0.50	0.54	0.08	0.07
Cr	17.71	24.14	23.66	26.14	0.21	22.96	18.44	21.52	20.57
Cu	12.24	15.02	23.45	19.04	0.08	13.31	14.71	8.99	5.93
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	28.86	30.95	49.91	64.87	0.42	44.75	38.75	58.86	64.58
Pb	14.21	22.11	12.91	4.48	0.03	16.10	15.69	4.05	7.46
Se	ND	ND	ND	ND	ND	ND	ND	ND	ND
Zn	36.84	49.75	13.66	42.47	0.50	60.20	63.76	50.37	43.91

ND = Not determined.

TABLE 33. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE L

Boring and sample	1C1	1C2	1C3	1C4	2C1	2C2	2C3	2C4
Elevation (m)	132.02	130.48	129.56	127.48	130.25	123.39	122.91	121.98
Depth below sludge/soil interface (m)	-1.45	0.09	1.01	3.10	-7.24	-0.38	0.10	1.03
Ht. above water table (m)	10.75	9.21	8.29	6.21	8.49	1.63	1.15	0.22
Conc. (mg/kg dry wt.)								
Ca	6949.27	BDL	BDL	97063.43	10023.27	14768.90	38920.79	60524.81
Fe	14792.03	15800.24	27879.87	5545.00	16277.46	19654.31	10056.00	8166.02
K	2134.42	547.46	580.23	186.22	1811.31	1572.66	351.60	253.00
Mg	9331.88	12811.01	21604.33	220551.42	9752.59	8048.80	85932.42	143099.23
Mn	75.79	374.03	659.38	377.58	90.16	88.01	572.14	485.39
Na	368.31	50.39	19.55	85.31	332.75	320.58	129.90	103.08
As	CI	CI	CI	CI	CI	CI	CI	CI
B	384.20	11.44	8.74	4.59	431.41	416.30	8.74	6.94
Be	3.20	1.31	0.60	0.28	2.34	2.53	0.22	0.23
Cd	9.13	1.15	2.13	BDL	9.77	3.51	BDL	BDL
Cr	23.85	11.39	12.49	5.48	22.35	19.72	4.85	5.22
Cu	19.56	8.54	16.67	4.12	16.99	13.51	5.92	5.64
Hg	ND	ND	ND	ND	ND	ND	ND	ND
Ni	20.58	17.79	15.67	14.18	19.19	17.30	12.46	13.26
Pb	29.78	17.08	9.26	3.64	19.33	28.23	4.38	2.91
Se	1.08	0.88	BDL	0.18	0.99	0.55	0.52	0.44
Zn	363.20	47.19	56.32	15.97	152.64	104.84	22.56	20.36

ND = Not determined.

CI = Chemical interference.

BDL = Below detection limits.

TABLE 34. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE L

Boring and sample	3C5	4C1	4C2	4C3	4C4	4C5	5C1	5C2	5C3
Elevation (m)	121.30	132.97	128.70	124.60	123.55	121.42	130.60	129.69	127.59
Ht. above water table (m)	-0.41	10.93	6.66	2.56	1.51	-0.62	9.22	8.31	6.21
Position in groundwater gradient	Updip	Updip	Updip	Updip	Updip	Updip	Downdip	Downdip	Downdip
Conc. (mg/kg dry wt.)									
Ca	99471.09	BDL	87854.64	60889.13	48323.21	118154.98	64425.96	107457.12	92233.30
Fe	2457.31	20183.24	5900.45	6006.69	5968.15	5753.95	7869.52	10247.30	6132.68
K	169.94	468.40	180.37	147.95	100.46	147.87	183.01	276.67	128.25
Mg	261724.70	19211.41	380088.13	129438.18	111607.54	199605.68	182993.14	513523.15	206783.56
Mn	168.76	465.60	4390.36	225.43	214.69	263.20	357.30	490.53	275.27
Na	83.99	28.84	101.18	61.03	53.95	94.26	82.99	139.33	85.50
As	CI	CI	CI	CI	CI	CI	CI	CI	CI
B	5.30	5.93	8.25	4.74	3.10	5.58	4.72	1.21	7.01
Be	0.21	0.44	0.49	0.32	0.28	0.42	0.18	0.34	0.27
Cd	BDL	1.60	1.51	1.04	1.52	1.16	BDL	1.63	0.99
Cr	5.87	9.32	5.96	4.62	4.49	6.36	4.08	11.43	6.63
Cu	3.63	15.90	6.23	3.13	3.47	3.56	7.62	10.05	5.27
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	8.73	18.49	32.43	9.39	7.68	6.99	13.79	15.88	9.77
Pb	2.02	69.91	4.40	4.81	4.74	3.33	1.97	14.74	4.78
Se	0.48	0.82	0.43	0.43	0.50	0.52	BDL	0.43	0.22
Zn	13.77	55.23	22.61	15.72	16.00	15.34	21.92	39.01	17.10

(continued)

TABLE 34 (CONTINUED)

Boring and sample	5C4	5C5	5C6	6C5	7C1	7C2	7C3	7C4	7C5
Elevation (m)	125.45	123.44	121.30	121.64	133.22	128.89	124.98	123.94	121.90
Ht. above water table (m)	4.07	2.06	-0.08	0.33	11.37	7.04	3.13	2.09	0.05
Position in groundwater gradient	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip
Conc. (mg/kg dry wt.)									
Ca	59016.09	75206.65	113848.83	83497.61	BDL	118910.67	51865.90	70760.66	61700.25
Fe	5846.68	8301.94	5710.91	6697.04	11710.84	5426.97	5507.47	6913.72	11039.06
K	116.77	84.52	128.68	183.00	220.34	146.91	96.65	161.54	159.30
Mg	201778.52	141170.26	237000.00	139865.94	7085.34	364173.30	242151.06	200775.64	109450.09
Mn	372.63	291.53	194.31	114.23	BDL	452.12	140.20	148.76	115.32
Na	71.00	61.30	87.02	74.60	19.34	104.50	15.61	73.01	60.59
As	CI	CI	CI	CI	CI	CI	CI	CI	CI
B	5.80	3.17	4.50	4.72	2.77	6.80	2.90	4.96	4.76
Be	0.23	0.22	0.31	0.27	0.28	0.28	0.19	0.27	0.25
Cd	1.02	BDL	0.96	BDL	1.12	BDL	BDL	0.95	BDL
Cr	5.66	4.87	6.58	7.08	5.28	7.31	4.94	6.36	6.01
Cu	5.86	3.84	9.16	6.11	8.38	5.72	4.85	5.77	5.66
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	14.54	12.22	9.50	10.51	10.55	12.70	10.07	9.20	9.66
Pb	2.04	2.29	2.91	5.83	5.37	5.17	BDL	4.56	4.89
Se	0.13	0.16	0.33	0.26	BDL	0.23	BDL	0.16	BDL
Zn	18.03	15.05	17.31	20.98	31.60	16.76	BDL	20.17	17.40

ND = Not determined.

CI = Chemical interference.

BDL = Below detection limits.

TABLE 35. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE M

Boring and sample	1C1	1C2	1C3	1C4	4C1	4C2	4C3	4C4	4C5
Elevation (m)	222.77	220.81	218.96	217.73	221.98	221.07	218.93	217.41	216.65
Depth below sludge/soil interface (m)	-1.89	0.07	1.92	3.15	0.09	1.00	3.14	4.66	5.42
Ht. above water table (m)	5.96	4.00	2.15	0.92	5.03	4.12	1.98	0.46	-0.30
Conc. (mg/kg dry wt.)									
Ca	122338.27	6844.07	8719.09	3444.40	46703.96	3446.29	11764.94	21432.61	3014.33
Fe	19277.54	5520.36	8001.76	2726.38	25481.03	33521.89	5164.61	7976.06	2458.31
K	1167.77	330.44	418.27	123.83	1464.54	4352.11	264.21	546.09	126.10
Mg	66729.97	21571.57	31724.15	9365.43	31826.49	52473.91	27916.81	47758.52	8290.52
Mn	250.18	93.29	143.40	40.94	314.74	523.64	100.64	150.65	23.34
Na	840.61	90.21	102.04	49.95	366.71	267.58	70.79	130.16	48.37
As	CI	CI	CI	CI	CI	CI	CI	CI	CI
B	225.06	3.21	3.92	0.72	118.48	18.89	3.03	8.63	1.93
Be	4.21	0.22	0.29	0.10	2.08	1.61	0.12	0.20	BDL
Cd	2.09	BDL	1.01	BDL	7.52	4.55	BDL	BDL	BDL
Cr	29.54	3.74	6.02	1.66	24.98	26.40	5.35	7.25	1.93
Cu	29.66	1.97	5.59	BDL	38.40	24.68	1.77	3.31	BDL
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	31.57	7.13	9.24	3.53	37.64	31.07	7.19	9.07	3.31
Pb	53.75	2.21	2.94	2.47	38.06	15.62	2.84	4.89	1.38
Se	0.33	0.10	0.11	0.06	2.42	0.94	0.05	BDL	0.16
Zn	95.46	17.84	23.74	6.88	351.72	98.70	19.14	24.96	8.64

ND = Not determined.

CI = Chemical interference.

BDL = Below detection limits.

TABLE 36. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE M

Boring and sample	2C1	2C2	2C3	2C4	3C1	3C2	3C3	3C4
Elevation (m)	221.78	220.87	218.72	217.97	221.70	220.79	218.64	217.89
Ht. above water table (m)	3.96	3.05	0.90	0.15	4.60	3.69	1.54	0.79
Position in groundwater gradient	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip
Conc. (mg/kg dry wt.)								
Ca	4900.45	7084.11	23589.01	12068.92	7891.82	12529.70	22318.88	27196.65
Fe	23119.05	4880.78	13138.22	6123.80	20179.09	11676.24	10213.72	8269.48
K	2588.54	290.99	1031.18	328.09	1997.93	1178.64	856.82	616.17
Mg	61255.61	26588.65	68294.45	36791.23	59538.29	48418.57	69226.36	61192.46
Mn	615.46	102.21	261.65	109.83	520.40	269.63	263.80	134.23
Na	92.87	63.22	124.68	70.30	99.90	114.68	125.78	108.79
As	CI	CI	CI	CI	CI	CI	CI	CI
B	8.89	2.34	6.00	2.18	9.93	6.20	6.45	4.92
Be	1.24	0.23	0.48	BDL	0.74	0.40	0.40	0.32
Cd	2.66	0.95	1.67	BDL	2.11	1.89	1.29	1.07
Cr	18.05	4.49	10.76	5.07	17.75	11.21	9.81	7.93
Cu	19.56	1.62	14.94	2.57	24.27	9.86	7.20	4.81
Hg	ND	ND	ND	ND	ND	ND	ND	ND
Ni	22.58	8.42	20.38	7.62	22.34	13.21	11.12	11.78
Pb	14.82	2.32	8.99	2.21	9.99	5.31	4.73	4.25
Se	0.06	0.07	0.25	0.20	0.13	0.17	0.07	0.13
Zn	77.56	27.15	46.84	18.86	67.43	41.62	32.44	31.96

(continued)

TABLE 36 (CONTINUED)

Boring and sample	5C4	6C1	6C4	7C1	7C2	7C3	7C4
Elevation (m)	217.17	220.77	216.14	221.09	220.18	218.05	216.52
Ht. above water table (m)	0.03	4.60	-0.03	4.84	3.93	1.80	0.27
Position in groundwater gradient	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip	Downdip
Conc. (mg/kg dry wt.)							
Ca	4795.95	11083.92	9614.80	6826.47	2758.40	4481.85	19333.84
Fe	3386.38	17960.39	4814.58	11194.91	22964.75	22405.08	8726.38
K	167.78	2164.50	240.37	1415.46	2822.80	2573.74	487.33
Mg	15440.91	48485.67	28060.94	31354.10	48941.54	46148.41	47835.09
Mn	17.62	511.25	59.26	222.11	395.98	483.61	170.35
Na	38.63	95.15	60.96	79.73	89.08	126.47	112.61
As	CI	CI	CI	CI	CI	CI	CI
B	1.33	6.73	1.34	4.87	7.87	7.53	2.70
Be	0.10	0.68	BDL	0.48	1.17	0.98	0.13
Cd	BDL	2.98	1.17	2.13	3.49	3.15	1.62
Cr	2.11	14.07	3.94	9.91	20.24	18.92	5.87
Cu	1.15	15.48	1.70	9.05	17.71	17.08	5.21
Hg	ND	ND	ND	ND	ND	ND	ND
Ni	4.45	19.49	7.28	12.13	22.80	22.68	10.40
Pb	2.35	13.59	2.24	10.75	11.81	13.31	4.98
Se	0.18	0.21	0.17	0.12	0.17	0.19	0.10
Zn	12.92	71.94	17.37	72.65	72.77	71.22	30.10

ND = Not determined.
CI = Chemical interference.
BDL = Below detection limits.

samples beneath and from comparable depths outside the disposal area are given in Table 37. At site K, significant differences in concentrations in the nitric acid digests were observed only for iron, sodium and copper. All three metals showed a decrease in concentration in soil below the disposal site. The reduction in sodium noted below the landfill is very likely related to the replacement of sodium by calcium in clays beneath the disposal pond. Mobiliation and ion exchange may also account for the slightly smaller amounts of iron and copper reported in the soil samples from below the pond. The only other significant difference between samples inside and outside any of the other disposal areas was an increase in boron concentration in soil samples below the disposal pit at site L. Boron is a common contaminant associated with leachate from ash. Ash was co-disposed with sludge at site L; therefore the occurrence of boron was not unexpected. Boron also was found in significantly larger quantities in the distilled water extracts from soil under site L.

The lack of significant increases in sludge-derived constituents in soil beneath the disposal areas indicates very little of the contaminating material is being trapped and removed as the leachate passes through into the groundwater. The major materials derived from the FGC sludge/ash are in solution at high concentrations. Typical soils below the disposal sites showed few changes in composition that can be related to the passage of leachate through them. At only one site (site K) was there evidence that calcium was displacing other ions from the available exchange positions, and becoming fixed in the soil.

Vertical Variations of Concentrations in the Nitric Acid Digests of Soil Samples

For elements that showed a significant difference between experimental and control samples, a test was made for a significant relationship between the concentration of a particular constituent and sample elevation in the boring. As suggested by the model (Figure 1), those materials attenuated from the sludge leachate should show a positive correlation with elevation in experimental borings (those below the disposal area). A significant negative correlation would be predicted for those soil constituents that are being mobilized by the sludge leachate and moved down into the groundwater. In control borings the distribution of soil constituents depends upon the weathering processes; therefore, the concentration of any particular material could have a positive or negative correlation or have no correlation at all. The Spearman rank correlation coefficient was used to assess the strength of the association between concentration of a particular constituent and sample elevation. The results of these statistical tests are given in Tables 38 and 39. Plots of concentration versus sample elevation for all constituents in experimental borings that showed significant relationships with depth are shown in Figures 16 and 17. Significant trends in control borings are shown for contrast.

At site K, only iron in boring 2 showed a significant correlation with sample elevation. The amount of iron in the samples increased with increasing elevation. This is the effect which would be expected if iron were being added to the soil/sediment. At site L, boron showed a positive correlation in both borings one and two under the disposal pit. This increase is what would

TABLE 37. RESULTS OF RANDOMIZATION TEST ON NITRIC ACID DIGESTS OF SOIL SAMPLES DIRECTLY UNDER THE FGC DISPOSAL SITES AND AT COMPARABLE DEPTHS OUTSIDE THE SITES

Parameters	Site K	Site L	Site M
Ca	NS	NS	NS
Fe	S(decrease)*	NS	NS
K	ND	NS	NS
Mg	NS	NS	NS
Mn	NS	NS	NS
Na	S(decrease)	NS	NS
As	ND	ND	ND
B	ND	S(increase)	NS
Be	NS	NS	NS
Cd	NS	NS	NS
Cr	NS	NS	NS
Cu	S(decrease)	NS	NS
Hg	ND	ND	ND
Ni	NS	NS	NS
Pb	NS	NS	NS
Se	ND	NS	NS
Zn	NS	NS	NS

NS = Not significant at 80% confidence level.

S = Significant at 80% confidence level.

ND = Not determined.

* Refers to increase or decrease of constituent under disposal site relative to outside.

TABLE 38. CORRELATION OF CHEMICAL ANALYSES OF NITRIC ACID DIGESTS OF SOILS WITH SAMPLE ELEVATION AT SITE K

Boring	1	2	6	7
Fe	NS(0.40)	SN(-1.00)	SP(1.00)*	NS(0.80)
Na	NS(-0.40)	NS(0.40)	NS(0.50)*	NS(0.20)
Cu	NS(0.20)	NS(-0.40)	SP(1.00)*	NS(0.80)

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = No significant correlation.

* = Significance level reduced to 83% because of small sample size for this constituent in this boring.

Number in parentheses is the calculated value of r_s, the Spearman rank correlation coefficient.

TABLE 39. CORRELATION OF CHEMICAL ANALYSES OF NITRIC ACID DIGESTS OF SOILS WITH SAMPLE ELEVATION AT SITE L

Boring	1	2	4	5	7
B	SP(1.00)	SP(1.00)	NS(0.60)	NS(0.08)	NS(-0.30)

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = No significant correlation.

Number in parentheses is the calculated value of r_s, the Spearman rank correlation coefficient.

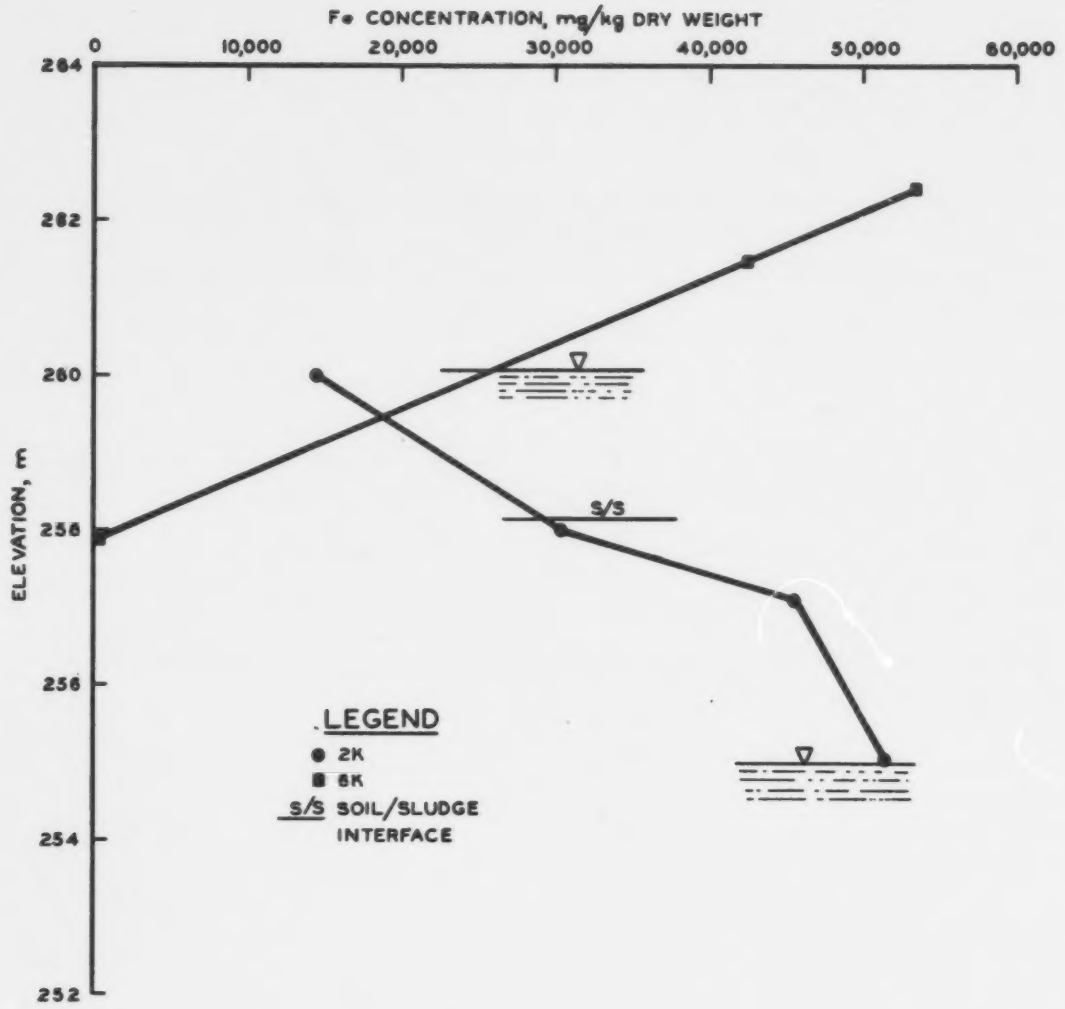

Figure 16. Variation of iron concentration in nitric acid digests of soil/sediment samples with elevation in borings 2 and 6 at site K.

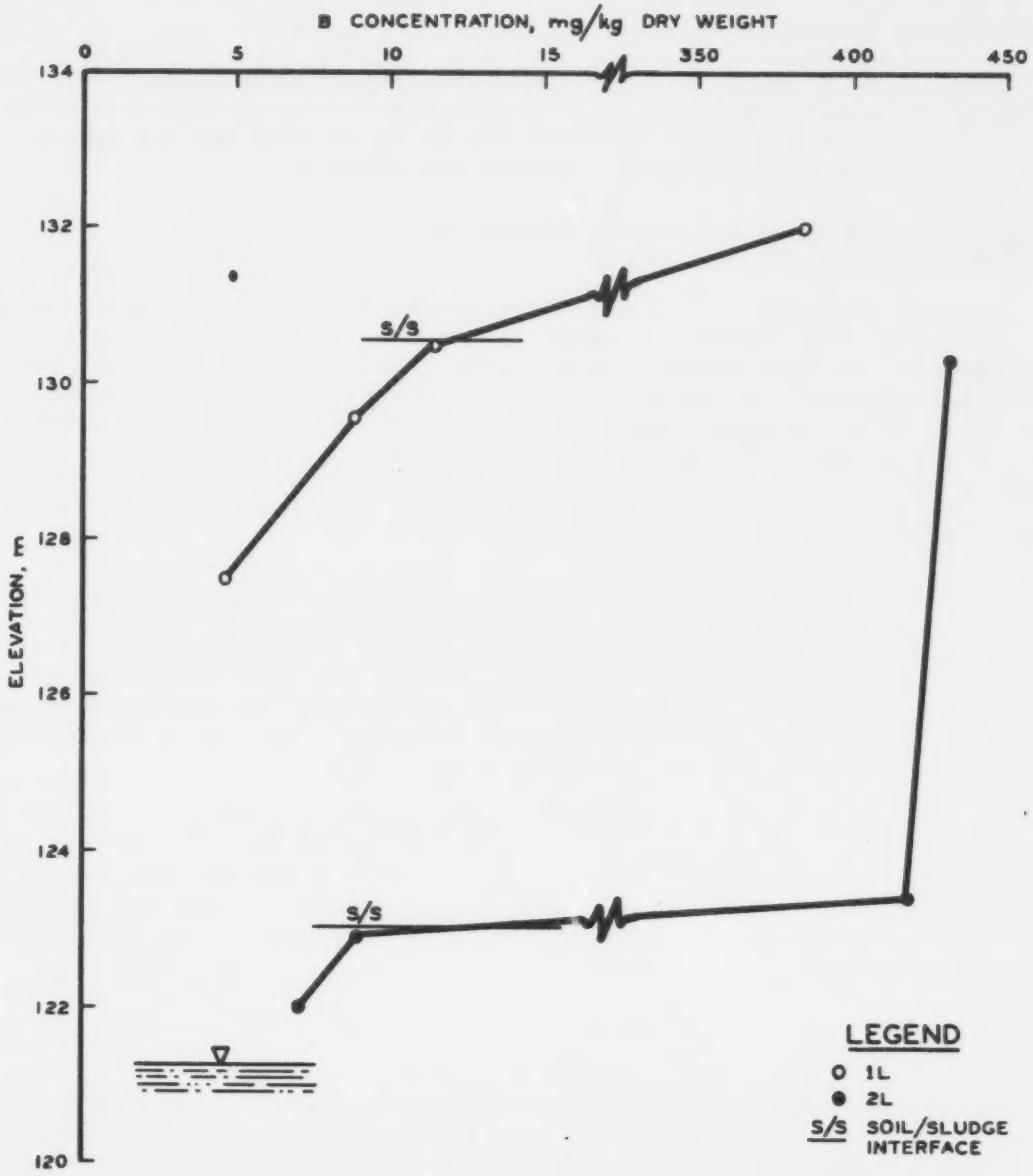

Figure 17. Variation of boron concentration of nitric acid digests of soil/sediment samples with elevation in borings 1 and 2 at site L.

be expected if boron was being added from the disposal pit.

As noted above, there was only slight evidence of attenuation. Only iron at site K and boron at site L showed the patterns indicating they were being removed by the soil. The most striking feature of the data was the lack of other demonstrable interaction of leachate with the soil.

Horizontal Variation in Nitric Acid Digests of Soil/Sediment Below the Water Table

Analyses of nitric acid digests of soil/sediment samples collected below the water table were examined in order to determine if contaminants were migrating with the groundwater flow below the disposal site. The model for groundwater movement assumes all significant lateral migration of contaminants takes place below the water table. The increased concentrations of contaminants in the nitric acid digests should be a measure of the attenuation occurring during lateral migration of the pollutants. Plots of metal concentrations in the nitric acid digests versus the positions of the borings are given in Figures 18-20.

At site K, all of the constituents measured in nitric acid digests of soil/sediment, with the exception of manganese, showed maximum levels underneath the disposal pond. This distribution pattern suggests that the materials being leached from the sludge (FGC wastes and ash) are being attenuated or contained in soils under the landfill. The sediments at this site are largely clays, shales and limestone that are impervious and could prevent dispersal of incoming constituents down the groundwater gradient.

Sites L and M are both underlain by porous sands and gravels. No consistent patterns could be found that related concentrations of various materials in the nitric acid digests to the position of the soil samples with respect to the disposal areas. There was no increase in contaminants under the disposal areas that could be interpreted as indicating that attenuation or containment of the pollutants had taken place.

SUMMARY

The physical testing data indicate two major types of sites were included in this study; one type underlain by impermeable materials, clay and shale, etc. (site K), and a second type underlain by relatively permeable, silty, sands and gravel with discontinuously distributed finer material included (sites L and M). At the site underlain by clay and shale the typical permeabilities or hydraulic conductivities were very low ($\sim 2 \times 10^{-8}$ cm/sec) and no change in permeability could be related to the presence of the sludge/ash disposal site. At site M, changes in permeability could be noted, but these changes appeared to be more related to the irregular occurrences of fine-grained materials (clays and silty sands) than to the presence of the disposal facility. Only at site L could variations in physical properties (permeability, dry density, water content, percent fines) measured in soil samples from test borings be related to the disposal of FGC sludge and ash.

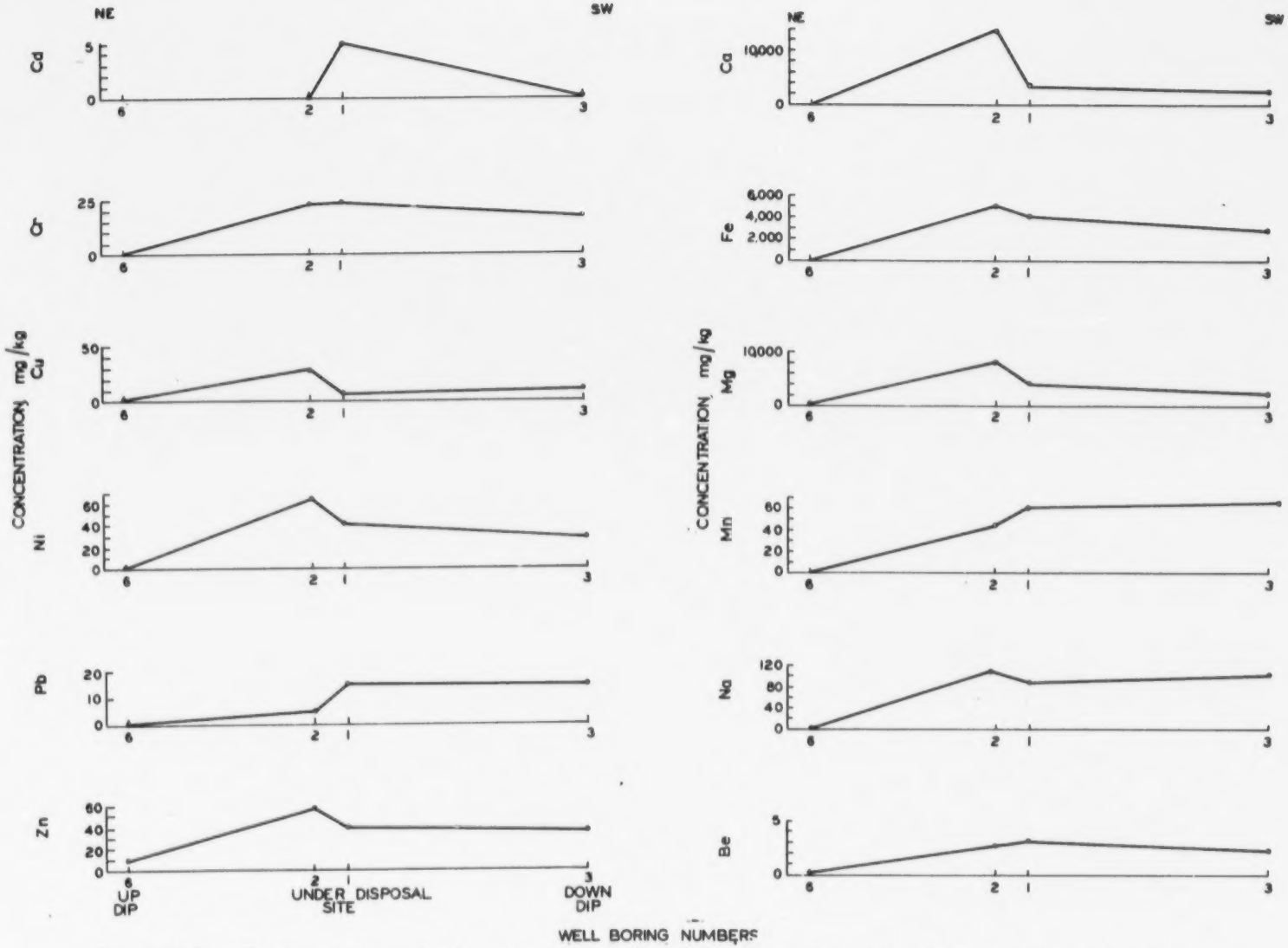

Figure 18. Horizontal variation in chemical composition of nitric acid digests at site K. BDL indicates below detection limits.

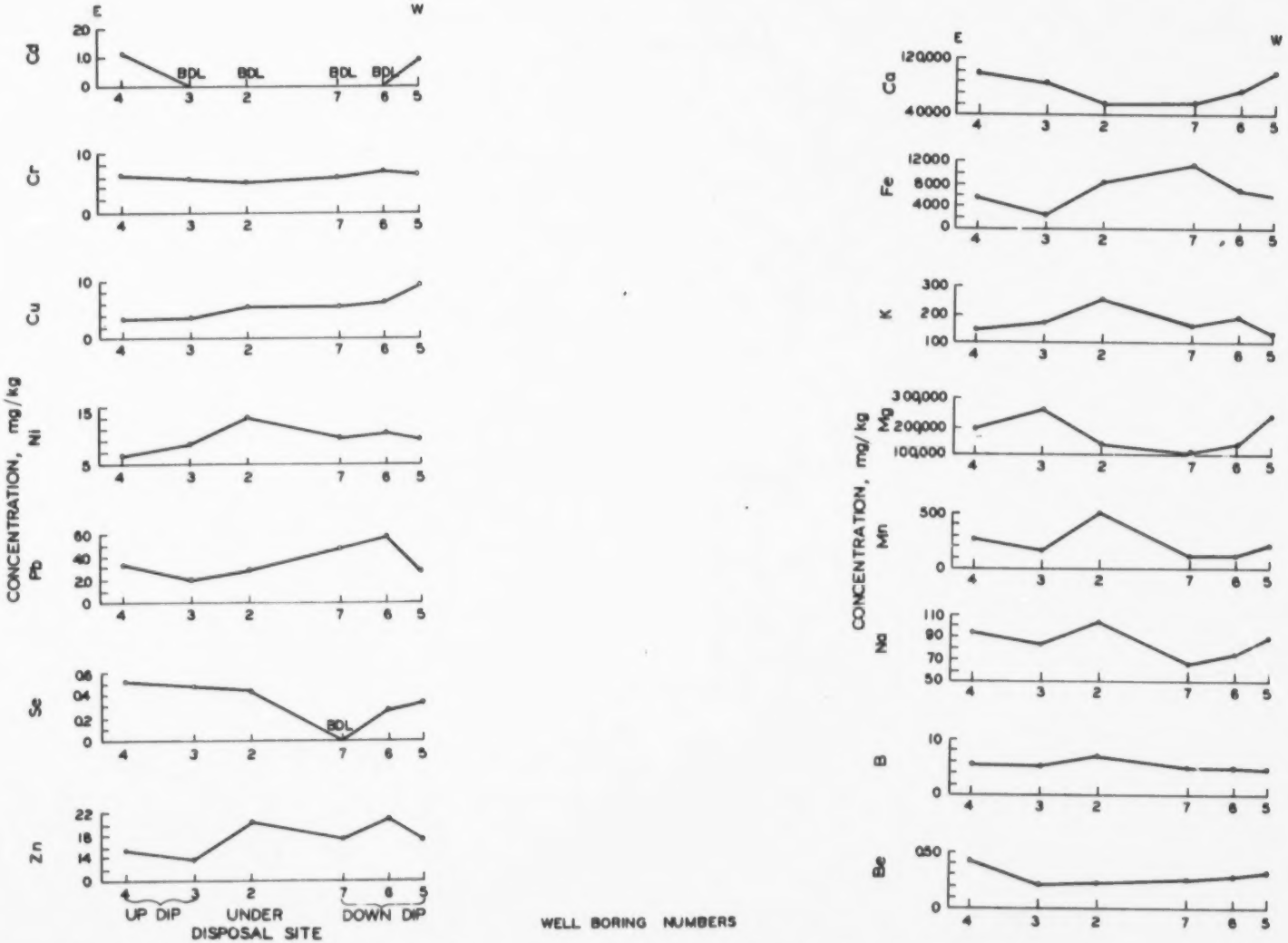

Figure 19. Horizontal variation in chemical composition of nitric acid digests at site L. BDL indicates below detection limits.

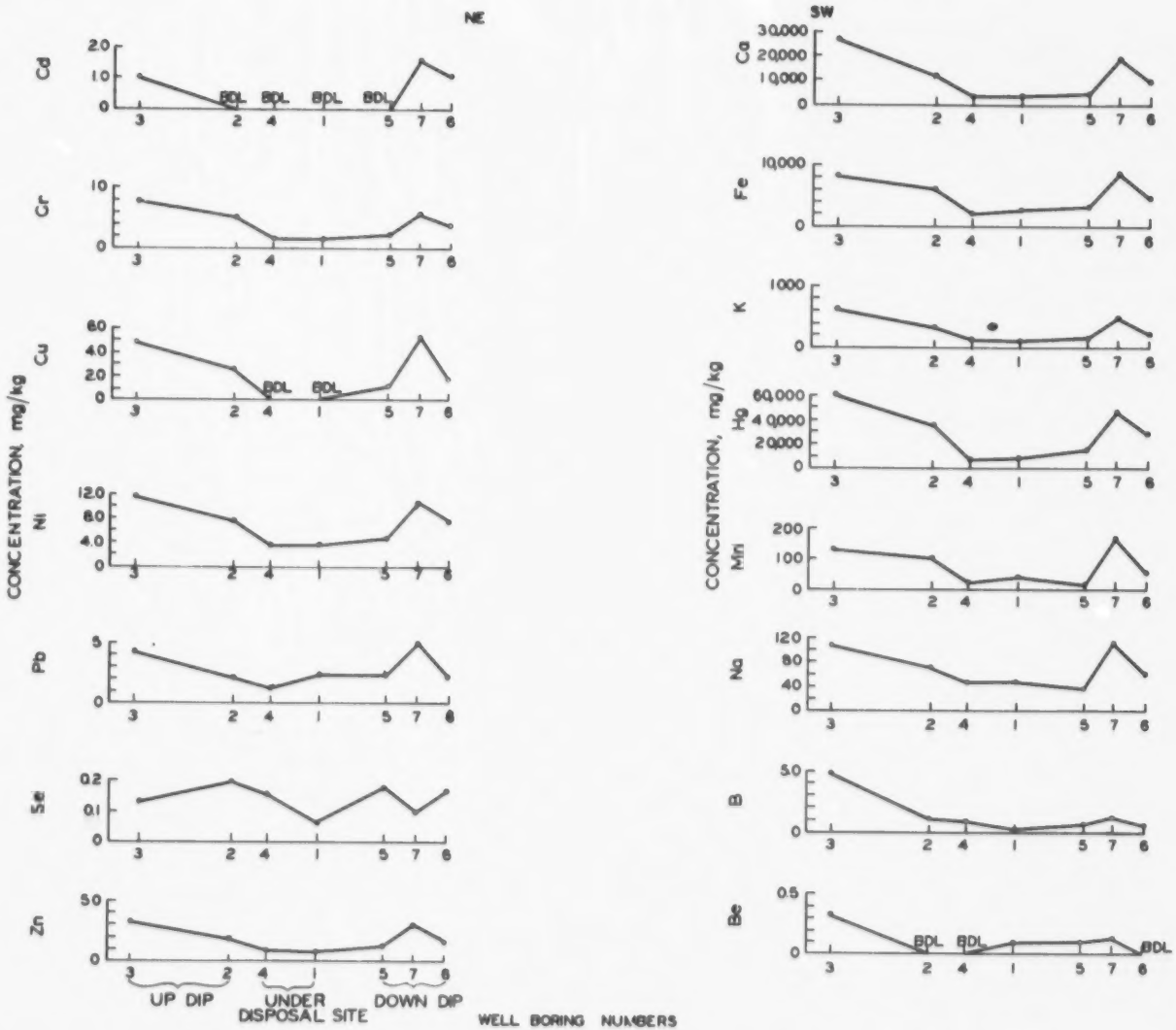

Figure 20. Horizontal variation in chemical composition of nitric acid digests at site M. BDL indicates below detection limits.

Although the potential of FGC sludge and ash for pollution of local groundwater has been noted, (13) no field evidence of such pollution occurring has been reported. At all three sites in this study, it could be shown that sludge/ash-derived constituents had migrated out of the immediate area of the disposal site and were found in local groundwater. The subsurface migration of FGC/ash-derived materials seemed to be most limited at the site where the pond was underlain by impermeable strata (site K). Although one boring outside the pond was severely contaminated, additional borings around the pond showed no groundwater when drilled to comparable depths. The only other boring from which a groundwater sample was obtained at this site was down the apparent groundwater gradient from the pond and near a large cooling lake. No contaminants from the pond were detected in this boring. At the other sites (L and M) which were underlain by sands and gravels, evidence of a typical pollution plume under and down the groundwater gradient from the disposal site was found.

The investigation of distilled water extracts and nitric acid digests of soil samples from underneath and around sludge/ash disposal sites indicates only slight changes in soil chemistry can be attributed to the presence of the disposal site. Evidently FGC sludge/ash leachates can move through the soils and sediments studied without appreciable interaction.

REFERENCES

1. Evans, R. J. Potential Solid Waste Generation and Disposal from Lime and Limestone Desulfurization Processes. U. S. Bureau of Mines, I. C. 8633, Washington, DC, 1974. 22 pp.

2. Michael Baker, Jr., Inc. State-of-the-Act of FGD Sludge Fixation. Final Report, Research Project 786-1. Electric Power Research Inst., Palo Alto, CA, 1978. 276 pp.

3. Lunt, R. R. and others. Evaluation of the Disposal of Flue Gas Desulfurization Wastes in Mines and the Ocean: Initial Assessment. EPA-600/7-77-051, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1977. 318 pp.

4. Princiotta, F. T. and W. H. Ponder. Current Status of SO_2 Control Technology. Paper presented at Lawrence Berkeley Laboratory Seminar on Sulfur, Energy and Environment, Berkeley, CA, April 1974.

5. Leo, P. P. and J. Rossoff. Control of Waste and Water Pollution from Power Plant Flue Gas Cleaning Systems: First Annual R and D Report. EPA-600/7-76-018, October 1976.

6. Ifeadi, C. N. and H. S. Rosenberg. Lime/Limestone Sludges--Trends in the Utility Industry. Proceedings, Symposium on Flue Gas Desulfurization, Atlanta, GA, November 1974. (as cited in 4)

7. Interess, E. Evaluation of the General Motors' Double Alkali SO_2 Control System. EPA-600/7-77-005, January 1977. (as cited in 5)

8. Esso Research and Engineering Co. Potential Pollutants in Fossil Fuels. NTIS. (as cited in 4)

9. Radian Corporation. The Environmental Effects of Trace Elements in the Pond Disposal of Ash and Flue Gas Desulfurization Sludge. Final Report, Research Project 202, Electric Power Research Inst., Palo Alto, CA, 1975.

10. Selmeczi, J. G. and R. G. Knight. Properties of Power Plant Waste Sludges. Paper presented at Third International Ash Utilization Symposium, Pittsburgh, PA, March 1973.

11. A Laboratory and Pilot Plant Study of the Dual Alkali Process for SO_2 Control. Unpublished results under EPA Contract 68-02-1071. (as cited in 4)

12. Nemerow, N. L. Liquid Waste of Industry--Theories, Practices and Treatment. Addison-Wesley, Reading, MA, 1971. 584 pp.

13. Rossoff, J. and R. C. Rossi. Disposal of By-Products from Non-Regenerable Flue Gas Desulfurization Systems: Inital Report. EPA-650/2-74-037-a, U. S. Environmental Protection Agency, Washington, DC, May 1974. 274 pp.

14. Leo, P. P., R. B. Fling, and J. Rossoff. Flue Gas Desulfurization Waste Disposal Study at the Shawnee Power Station. In: Proceedings: Symposium on Flue Gas Desulfurization--Hollywood, FL, November 1977. (Vol. II) EPA-600/7-78-058b. U. S. Environmental Protection Agency, Research Triangle Park, NC, 1978. pp. 496-536

15. Fry, Z. B. The Use of Liner Materials for Selected FGD Waste Ponds. In: Land Disposal of Hazardous Wastes. EPA-600/9-78-016, U. S. Environmental Protection Agency, Cincinnati, OH, 1978. pp. 256-272.

16. Fling, R. B. and others. Disposal of Flue Gas Cleaning Wastes; EPA Shawnee Evaluation--Initial Report. EPA-600/2-76070, U. S. Environmental Protection Agency, Washington, DC, March 1976.

17. Barrier, J. W., H. L. Faucett, and L. J. Henson. Economic Assessment of FGD Sludge Disposal Alternatives. Jour. Environmental Engineering Div. Proc. Am. Soc. Civil Engineers. 104(EE5):951-996, 1978.

18. Siegel, Sidney. Nonparametric Statistics for the Behaviorial Sciences. McGraw-Hill Book Co., New York, 1956. 312 pp.

19. Siddiqui, and R. R. Parizek. Application of Nonparametric Statistical Tests in Hydrogeology. Groundwater, 10(2):26-31, 1972.

20. U. S. Army Engineer, Waterways Experiment Station. The Unified Soil Classification System. Tech. Memorandum No. 3-257, Vol. 1, USAE Waterways Experiment Station, Vicksburg, MS, 1960. 30 pp.

21. Levinson, A. A. Introduction to Exploration Geochemistry. Applied Publ. Co., Ltd. Calgary, Canada, 1974. 612 pp.

22. Foster, J. R. The Reduction of Matrix Effects in Atomic Absorption Analysis and the Efficiency of Selected Extractions on Rock Forming Minerals. In: Geochemical Exploration, The Canadian Institute of Mining and Metallurgy. Special Vol. 11, Ottawa, Canada, 1971. pp. 554-560.

23. U. S. Dept. of the Army. Laboratory Soils Testing. Engineering Manual EM 1110-2-1906, U. S. Dept. of the Army, Washington, DC, 1970. No Pagination.

24. U. S. Environmental Protection Agency. Manual of Methods of Chemical Analyses of Water and Wastes. EPA 652/6-74-003, U. S. Environmental Protection Agency, Cincinnati, OH, 1971. 298 pp.

25. National Academy of Sciences - National Academy of Engineering. Water Quality Criteria - 1972. EPA-R3-73-033, March 1973. 594 pp.

26. U. S. Department of the Interior. Report of the Committee on Water Quality Criteria. Reprinted by the Environmental Protection Agency, Washington, DC, 1968 (Reprinted 1972). 234 pp.

APPENDIX A
SUBSURFACE DATA FROM SITE K

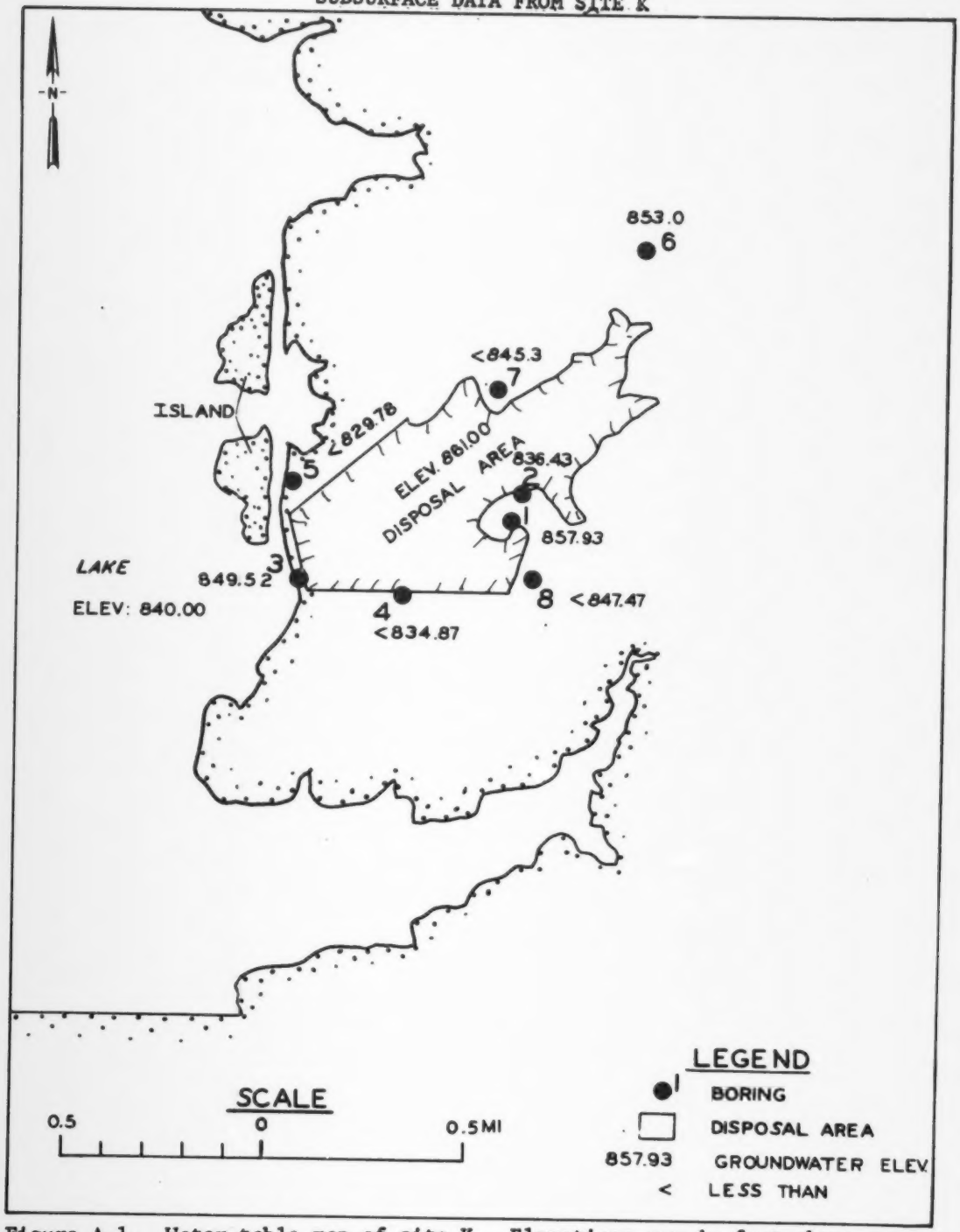

Figure A-1. Water table map of site K. Elevations are in feet above mean sea level. 1 foot = 0.305 meters.

TABLE A-1. LOG OF BORING 1 AT SITE K

Elevation above MSL* (m)	Depth (m)	Description
264.00 - 261.56	0.00 - 2.44	Bottom ash
261.00 - 260.49	2.44 - 3.51	Clay, brown, wet
260.49 - 258.36	3.51 - 5.64	Clay, brown, moist, hard
258.36 - 256.26	5.64 - 7.74	Shale, green, hard

* MSL = Mean sea level.

Water table elevation above MSL = 261.56 m

TABLE A-2. LOG OF BORING 2 AT SITE K

Elevation above MSL* (m)	Depth (m)	Description
263.67 - 261.84	0.00 - 1.83	Bottom ash
261.84 - 258.18	1.83 - 5.49	FGC sludge, wet
258.18 - 257.88	5.49 - 5.79	Clay, black
257.88 - 257.27	5.79 - 6.40	Clay, brown
257.27 - 255.13	6.40 - 8.54	Clay, brown, wet
255.13 - 254.52	8.54 - 9.15	Clay, green, dry, hard
254.52 - 253.61	9.15 - 10.06	Clay, green
253.61 - 253.46	10.06 - 10.21	Bedrock

* MSL = Mean sea level.

Water table elevation above MSL = 255.01 m

TABLE A-3. LOG OF BORING 3 AT SITE K

Elevation above MSL* (m)	Depth (m)	Description
259.15 - 251.53	0.00 - 7.62	Clay, dark brown with trace of black clay in lower portion
251.53 - 250.80	7.62 - 8.35	Shale, dark, weathered

* MSL = Mean sea level.

Water table elevation above MSL = 259.10 m

TABLE A-4. LOG OF BORING 4 AT SITE K

Elevation above MSL* (m)	Depth (m)	Description
263.53 - 262.92	0.00 - 0.61	Road bed
262.92 - 255.91	0.61 - 7.62	Clay, brown
255.91 - 254.54	7.62 - 8.99	Clay, black, wet

* MSL = Mean sea level.

Water table elevation above MSL = (dry hole)

TABLE A-5. LOG OF BORING 5 AT SITE K

Elevation above MSL* (m)	Depth (m)	Description
258.90 - 256.46	0.00 - 2.44	Clay, brown
256.46 - 252.99	2.44 - 5.91	Limestone, brown, weathered with some interbedded silty layers

* MSL = Mean sea level.

Water table elevation above MSL = (dry hole)

TABLE A-6. LOG OF BORING 6 AT SITE K

Elevation above MSL* (m)	Depth (m)	Description
265.24 - 264.33	0.00 - 0.91	Clay, black, wet
264.33 - 261.58	0.91 - 3.66	Clay, gray-brown, wet
261.58 - 260.06	3.66 - 5.18	Clay, brown with weathered limestone colluvial material
260.06 - 258.08	5.18 - 7.16	Shale, gray
258.08 - 256.86	7.16 - 8.38	Shale, gray, wet

* MSL = Mean sea level.

Water table elevation above MSL = 260.06 m

TABLE A-7. LOG OF BORING 7 AT SITE K

Elevation above MSL* (m)	Depth (m)	Description
265.24 - 264.33	0.00 - 0.91	Clay, black
264.33 - 262.50	0.91 - 2.74	Clay, brown
262.50 - 260.06	2.74 - 5.18	Clay, brown with decomposed limestone material
260.06 - 259.94	5.18 - 5.30	Competent layer
259.94 - 258.84	5.30 - 6.40	Shale, green, hard
258.84 - 257.70	6.40 - 7.54	Shale, gray, hard

* MSL = Mean sea level.

Water table elevation above MSL = (dry hole)

TABLE A-8. LOG OF BORING 8 AT SITE K

Elevation above MSL* (m)	Depth (m)	Description
265.24 - 264.63	0.00 - 0.61	Roadbed (bottom ash)
264.63 - 264.02	0.61 - 1.22	Clay, black, hard
264.02 - 263.41	1.22 - 1.83	Clay, brown, hard
263.41 - 262.50	1.83 - 2.74	Clay, brown, hard, moist
262.50 - 262.19	2.74 - 3.05	Clay, brown, with limestone pebbles
262.19 - 261.73	3.05 - 3.51	Clay, brown with shale chips
261.73 - 261.58	3.51 - 3.66	Competent layer
261.58 - 260.36	3.66 - 4.88	Clay, brown with shale chips
260.36 - 257.31	4.88 - 7.93	Shale, brown, hard
257.31 - 257.07	7.93 - 8.17	Shale, gray, hard

* MSL = Mean sea level.

Water table elevation above MSL = (dry hole)

TABLE A-9. LIST OF SAMPLES EXAMINED FROM SITE K

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of fill (m)	Elevation sludge/soil interface (m)	Sampled depth interval (m) From	To	Elevation of sampled intervals (m) From	To	Type of sample	Sample number
1	264.00	261.56	7.74	0	2.44	261.56	2.59	2.74	261.41	261.26	Chemical	1C1
							3.51	3.66	260.49	260.34	Chemical	1C2
							5.64	5.76	258.36	258.24	Chemical	1C3
							5.76	5.91	258.24	258.09	Physical	1P3
							7.62	7.74	256.38	256.26	Chemical	1C4
2	263.67	255.01	10.21	0	5.49	258.18	3.61	3.73	260.06	259.94	Chemical	2C1
							5.55	5.70	258.12	257.97	Chemical	2C2
							5.76	6.10	257.91	257.57	Physical	2P1
							6.40	6.59	257.27	257.08	Chemical	2C3
							8.53	8.66	255.14	255.01	Chemical	2C4
							8.72	8.93	254.95	254.74	Physical	2P3
3	259.15	259.10	8.35	NA	NA	NA	1.74	2.15	257.41	257.00	Physical	3P1
							4.79	5.29	254.36	253.86	Physical	3P3
							7.62	7.77	251.53	251.38	Chemical	3C5
							7.83	8.32	251.32	250.83	Physical	3P5
4	263.53	(dry)	8.99	NA	NA	NA	3.26	3.75	260.27	259.78	Physical	4P1
							7.83	8.29	255.70	255.24	Physical	4P4
5	258.90	(dry)	5.91	NA	NA	NA	1.52	1.68	257.38	257.22	Chemical	5C1
							1.74	2.20	257.16	256.70	Physical	5P1
							2.44	2.59	256.46	256.31	Chemical	5C2
							2.65	3.12	256.25	255.78	Physical	5P2
6	265.24	260.06	8.38	NA	NA	NA	2.74	2.90	262.50	262.34	Chemical	6C1
							2.96	3.41	262.28	261.83	Physical	6P1
							3.66	3.81	261.58	261.43	Chemical	6C2
							3.87	4.91	261.37	260.33	Physical	6P2
							7.32	7.39	257.92	257.85	Chemical	6C3
7	265.24	(dry)	7.54	NA	NA	NA	2.74	2.90	262.50	262.34	Chemical	7C1
							2.96	3.31	262.28	261.93	Physical	7P1
							3.96	4.11	261.28	261.13	Chemical	7C2
							5.79	5.91	259.45	259.33	Chemical	7C3
							7.32	7.48	257.92	257.76	Chemical	7C4

NA = Not applicable

Note: All elevations are given with respect to mean sea level.

APPENDIX B
SUBSURFACE DATA FROM SITE L

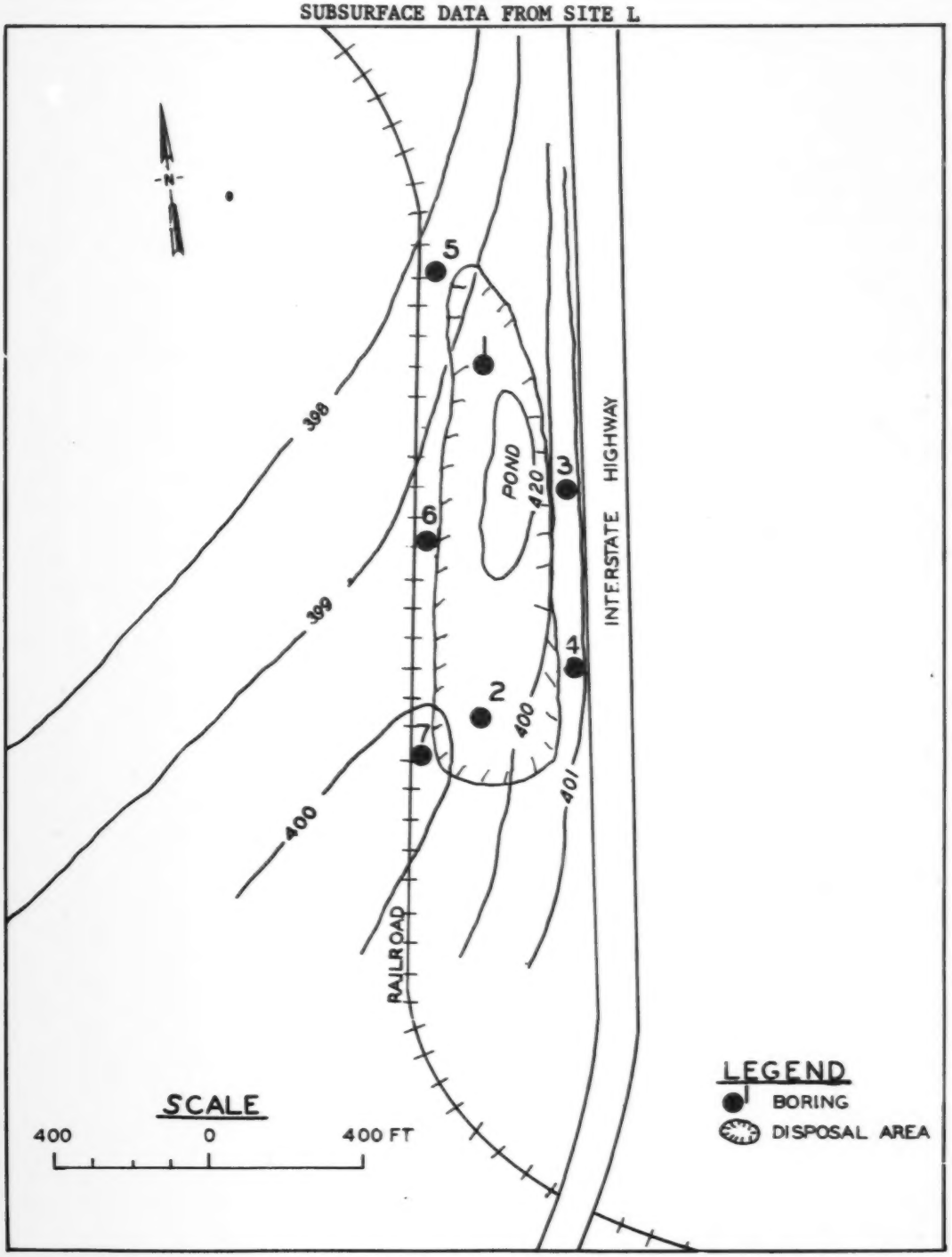

Figure B-1. Water table map of site L. Elevations are in feet above mean sea level. 1 foot = 0.305 meters.

TABLE B-1. LOG OF BORING 1 AT SITE L

Elevation above MSL* (m)	Depth (m)	Description
133.47 - 130.57	0.00 - 2.90	Fill (FGC sludge)
130.57 - 127.68	2.90 - 5.79	Clay, light gray to light brown, silty
127.68 - 127.53	5.79 - 5.94	Sand, fine to coarse, silty with small gravel
127.53 - 126.00	5.94 - 7.47	Gravel, small to large
126.00 - 119.90	7.47 - 13.57	Sand, fine to coarse, silty, with small gravel, light tan

*MSL = Mean sea level.

Water table elevation above MSL = 121.27 m

TABLE B-2. LOG OF BORING 2 AT SITE L

Elevation above MSL* (m)	Depth (m)	Description
137.49 - 137.19	0.00 - 0.30	Backfill (clay)
137.19 - 123.01	0.30 - 14.48	Fill (FGC sludge)
123.01 - 122.09	14.48 - 15.40	Sand, fine, silty with gravel, dark tan
122.09 - 120.87	15.40 - 16.62	Sand, fine to coarse, with gravel, wet

* MSL = Mean sea level.

Water table elevation above MSL = 121.85 m

TABLE B-3. LOG OF BORING 3 AT SITE L

Elevation above MSL* (m)	Depth (m)	Description
133.70 - 131.26	0.00 - 2.44	Clay, brown
131.26 - 129.74	2.44 - 3.96	Sand, wet, dark brown
129.74 - 125.16	3.96 - 8.54	Sand, fine to coarse with some gravel, damp, dark brown
125.16 - 123.34	8.54 - 10.36	Sand, fine to coarse, some gravel, damp, light tan
123.34 - 121.50	10.36 - 12.20	Sand, fine to coarse, gravely, moist, light tan
121.50 - 119.68	12.20 - 14.02	Sand, fine to medium, some gravel, wet, light tan

* MSL = Mean sea level.

Water table elevation above MSL = 121.58 m

TABLE B-4. LOG OF BORING 4 AT SITE L

Elevation above MSL* (m)	Depth (m)	Description
136.71 - 133.05	0.00 - 3.66	Clay, brown
133.05 - 131.47	3.66 - 5.24	Sand, fine, silty, light brown
131.47 - 124.67	5.24 - 12.04	Sand, fine to coarse with small to large gravel
124.67 - 121.16	12.04 - 15.55	Sand, fine to coarse with small gravel

* MSL = Mean sea level.

Water table elevation above MSL = 122.05 m

TABLE B-5. LOG OF BORING 5 AT SITE L

Elevation above MSL* (m)	Depth (m)	Description
133.73 - 132.51	0.00 - 1.22	Silt, sandy with gravel
132.51 - 131.90	1.22 - 1.83	Clay, silty, light brown
131.90 - 130.83	1.83 - 2.90	Gravel, clayey
130.83 - 130.76	2.90 - 2.97	Gravel, sandy
130.76 - 128.24	2.97 - 5.49	Sand, fine to coarse, silty with small to large gravel dark tan
128.24 - 127.79	5.49 - 5.94	Gravel, small to large
127.79 - 125.68	5.94 - 8.05	Sand, fine to coarse with small to large gravel
125.68 - 121.53	8.05 - 12.20	Sand, fine to coarse with gravel
121.53 - 119.43	12.20 - 14.30	Sand, fine to coarse, with some gravel, moist

* MSL = Mean sea level.

Water table elevation above MSL = 121.38 m

TABLE B-6. LOG OF BORING 6 AT SITE L

Elevation above MSL* (m)	Depth (m)	Description
137.34 - 133.07	0.00 - 4.27	Clay, light brown
133.07 - 131.85	4.27 - 5.49	Sand with gravel
131.85 - 124.84	5.49 - 12.50	Sand, fine to coarse with small to large gravel
124.84 - 123.93	12.50 - 13.41	Sand, fine to coarse with gravel
123.93 - 121.79	13.41 - 15.55	Sand, fine to coarse, with gravel, damp
121.79 - 120.57	15.55 - 16.77	Sand, fine to coarse with some gravel, damp

* MSL = Mean sea level.

Water table elevation above MSL = 121.30 m

TABLE B-7. LOG OF BORING 7 AT SITE L

Elevation above MSL* (m)	Depth (m)	Description
137.58 - 133.31	0.00 - 4.27	Clay
133.31 - 130.87	4.27 - 6.71	Sand, fine, silty, light brown
130.87 - 128.74	6.71 - 8.84	Sand, fine to coarse, with small to large gravel
128.74 - 126.00	8.84 - 11.58	Gravel, small to large
126.00 - 125.08	11.58 - 12.50	Sand, fine to coarse, with gravel
125.08 - 120.81	12.5 - 16.77	Sand, fine to coarse with some gravel

* MSL = Mean sea level.

Water table elevation above MSL = 121.85 m

TABLE B-8. LIST OF SAMPLES EXAMINED FROM SITE L

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of fill (m)	Elevation sludge/soil interface (m)	Sampled depth interval (m) From	To	Elevation of sampled intervals (m) From	To	Type of sample	Sample number
1	133.47	121.27	13.57	0	2.90	130.57	0.00	2.90	133.47	130.57	Chemical	1C1
							2.90	3.08	130.57	130.39	Chemical	1C2
							3.14	3.81	130.33	129.66	Physical	1P1
							3.81	3.99	129.66	129.48	Chemical	1C3
							5.94	6.04	127.53	127.43	Chemical	1C4
2	137.49	121.85	16.62	0.30	14.18	123.01	7.18	7.30	130.31	130.19	Chemical	2C1
							13.80	14.40	123.69	123.09	Chemical	2C2
							14.48	14.66	123.01	122.83	Chemical	2C3
							14.72	14.78	122.77	122.71	Physical	2P1
							15.39	15.61	122.10	121.88	Chemical	2C4
							15.67	14.97	121.82	121.52	Physical	2P2
3	133.70	121.58	14.02	NA	NA	NA	6.64	6.95	127.06	126.75	Physical	3P1
							12.20	12.59	121.50	121.11	Chemical	3C5
4	136.71	122.05	15.55	NA	NA	NA	3.66	3.81	133.05	132.90	Chemical	4C1
							3.87	4.30	132.84	132.41	Physical	4P1
							7.92	8.08	128.79	128.63	Chemical	4C2
							8.20	8.41	128.51	128.30	Physical	4P2
							12.04	12.16	124.67	124.55	Chemical	4C3
							12.95	13.35	123.76	123.36	Chemical	4C4
							15.09	15.48	121.62	121.23	Chemical	4C5
5	133.73	121.38	14.30	NA	NA	NA	2.97	3.28	130.76	130.45	Chemical	5C1
							3.81	4.27	129.92	129.46	Chemical	5C2
							5.94	6.19	127.79	127.54	Chemical	5C3
							8.05	8.50	125.68	125.23	Chemical	5C4
							10.06	10.52	123.67	123.21	Chemical	5C5
							12.19	12.65	121.54	121.08	Chemical	5C6
6	137.34	121.30	16.77	NA	NA	NA	4.51	4.69	132.83	132.65	Physical	6P1
							12.71	12.80	124.63	124.54	Physical	6P2
							15.54	15.85	121.80	121.49	Chemical	6C5
7	137.58	121.85	16.77	NA	NA	NA	4.27	4.45	133.31	133.13	Chemical	7C1
							4.51	4.91	133.07	132.67	Physical	7P1
							8.53	8.84	129.05	128.74	Chemical	7C2
							12.50	12.71	125.08	124.87	Chemical	7C3
							13.41	13.87	124.17	123.71	Chemical	7C4
							15.55	15.82	122.03	121.76	Chemical	7C5

NA = Not applicable.

Note: All elevations are given with respect to mean sea level.

APPENDIX C
SUBSURFACE DATA FROM SITE M

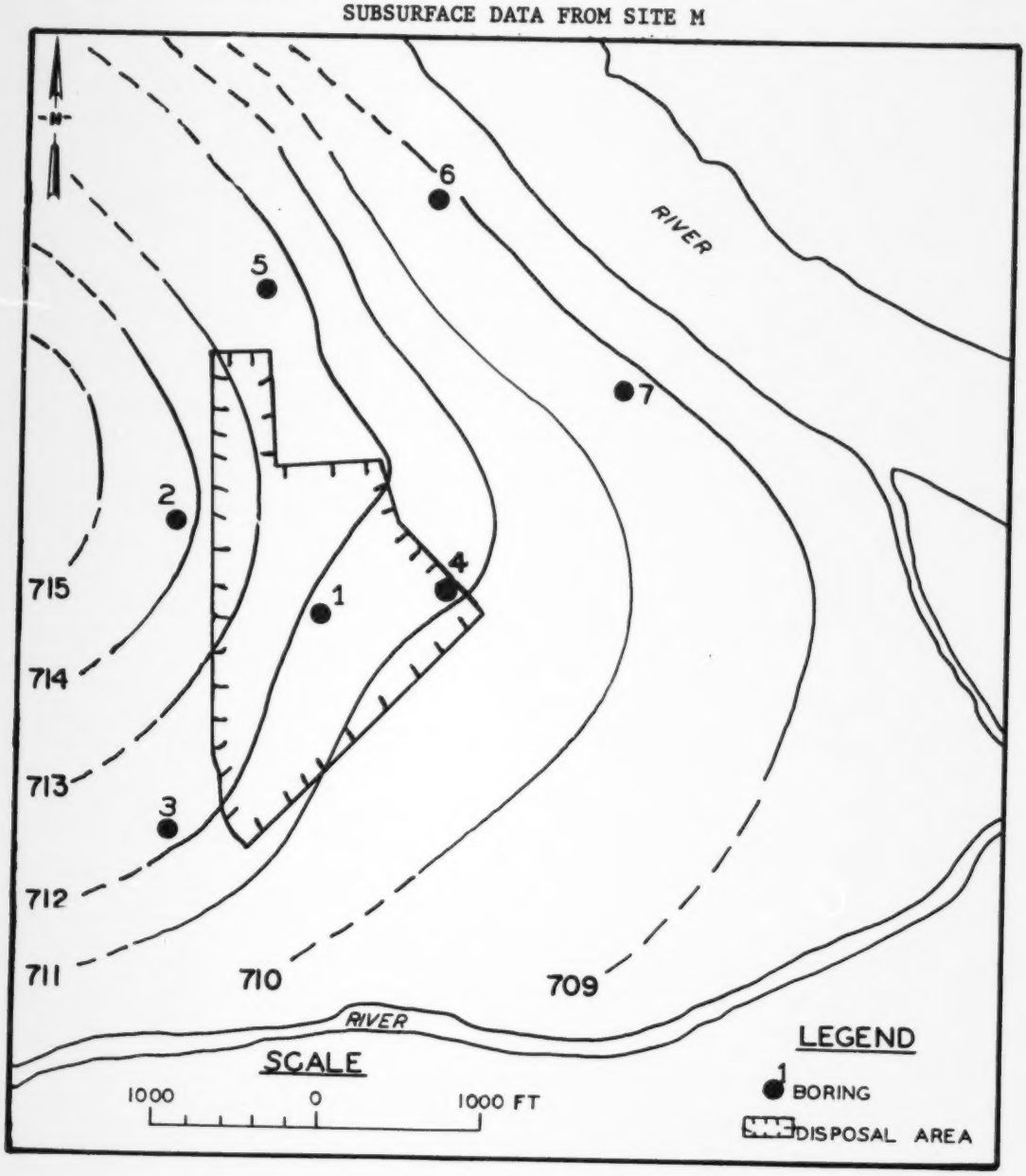

Figure C-1. Water table map of site M.
Elevations are in feet above mean sea level.
1 foot = 0.305 meters.

TABLE C-1. LOG OF BORING 1 AT SITE M

Elevation above MSL* (m)	Depth (m)	Description
224.68 - 220.88	0.00 - 3.80	Fill (FGC sludge)
220.88 - 217.82	3.80 - 6.86	Sand, fine, silty, light tan
217.82 - 216.14	6.86 - 8.54	Sand, fine, silty, light gray, wet

* MSL = Mean sea level.

Water table elevation above MSL = 216.82 m

TABLE C-2. LOG OF BORING 2 AT SITE M

Elevation above MSL* (m)	Depth (m)	Description
222.18 - 221.88	0.00 - 0.30	Top soil
221.88 - 221.42	0.30 - 0.76	Silt, light tan
221.42 - 218.83	0.76 - 3.35	Sand, fine, silty, light tan
218.83 - 216.39	3.35 - 5.79	Sand, fine, silty, wet, with trace of organic matter

* MSL = Mean sea level.

Water table elevation above MSL = 217.82 m

TABLE C-3. LOG OF BORING 3 AT SITE M

Elevation above MSL* (m)	Depth (m)	Description
222.10 - 221.80	0.00 - 0.30	Topsoil
221.80 - 220.88	0.30 - 1.22	Clay, silty, dark gray
220.88 - 220.58	1.22 - 1.52	Silt, light tan to dark gray
220.58 - 218.75	1.52 - 3.35	Sand, fine, silty, light tan
218.75 - 218.44	3.35 - 3.66	Clay with silt and sand, soft, dark gray
218.44 - 216.31	3.66 - 5.79	Sand, fine, wet

* MSL = Mean sea level.

Water table elevation above MSL = 217.10 m

TABLE C-4. LOG OF BORING 4 AT SITE M

Elevation above MSL* (m)	Depth (m)	Description
224.36 - 222.07	0.00 - 2.29	Fill (FGC sludge and soil)
222.07 - 219.02	2.29 - 5.34	Clay, silty, wet, dark gray
219.02 - 217.50	5.34 - 6.86	Sand, fine, silty, light tan
217.50 - 215.21	6.86 - 9.15	Sand, fine, silty, wet

* MSL = Mean sea level.

Water table elevation above MSL = 216.77 m

TABLE C-5. LOG OF BORING 5 AT SITE M

Elevation above MSL* (m)	Depth (m)	Description
222.14 - 221.84	0.00 - 0.30	Topsoil
221.84 - 221.23	0.30 - 0.91	Clay, silty, dark gray
221.23 - 217.26	0.91 - 4.88	Sand, fine, silty, light tan
217.26 - 216.19	4.88 - 5.95	Sand, fine, silty, wet

* MSL = Mean sea level.

Water table elevation above MSL = 217.14 m

TABLE C-6. LOG OF BORING 6 AT SITE M

Elevation above MSL* (m)	Depth (m)	Description
221.17 - 220.87	0.00 - 0.30	Topsoil
220.87 - 219.34	0.30 - 1.83	Clay, silty, dark to light brown
219.34 - 215.32	1.83 - 5.85	Sand, fine, silty, light tan

* MSL = Mean sea level.

Water table elevation above MSL = 216.17 m

TABLE C-7. LOG OF BORING 7 AT SITE M

Elevation above MSL* (m)	Depth (m)	Description
221.49 - 221.19	0.00 - 0.30	Topsoil
221.19 - 218.14	0.30 - 3.35	Clay, silty, dark gray
218.14 - 216.61	3.35 - 4.88	Clay, silty, dark gray, soft
216.61 - 215.33	4.88 - 6.16	Sand, fine, silty, wet, gray

* MSL = Mean sea level.

Water table elevation above MSL = 216.25 m

TABLE C-8. LIST OF SAMPLES EXAMINED FROM SITE M

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of fill (m)	Elevation sludge/soil interface (m)	Sampled depth interval (m) From	To	Elevation of sampled intervals (m) From	To	Type of sample	Sample number
1	224.68	216.82	8.54	0	3.80	220.88	1.52	2.13	223.16	222.55	Chemical	1C1
							3.79	3.95	220.89	220.73	Chemical	1C2
							4.01	4.27	220.67	220.41	Physical	1P1
							5.64	5.79	219.04	218.89	Chemical	1C3
							5.85	6.25	218.83	218.43	Physical	1P2
							6.86	7.04	217.82	217.64	Chemical	1C4
							7.10	7.62	217.52	217.06	Physical	1P3
2	222.18	217.82	5.79	NA	NA	NA	0.30	0.49	221.88	221.69	Chemical	2C1
							0.55	1.07	221.63	221.11	Physical	2P1
							1.22	1.40	220.96	220.78	Chemical	2C2
							3.35	3.57	218.83	218.61	Chemical	2C3
							4.11	4.30	218.07	217.88	Chemical	2C4
							4.36	4.82	217.82	217.36	Physical	2P4
3	222.10	217.10	5.79	NA	NA	NA	0.30	0.49	221.80	221.61	Chemical	3C1
							0.55	1.01	221.55	221.09	Physical	3P1
							1.22	1.40	220.88	220.70	Chemical	3C2
							1.46	1.77	220.64	220.33	Physical	3P2
							3.35	3.57	218.75	218.53	Chemical	3C3
							3.63	4.08	218.47	218.02	Physical	3P3
							4.11	4.30	217.99	217.80	Chemical	3C4
							4.36	4.88	217.74	217.22	Physical	3P4
4	224.36	216.77	9.15	0	2.29	222.07	2.29	2.47	222.07	221.89	Chemical	4C1
							2.53	3.05	221.83	221.31	Physical	4P1
							3.20	3.38	221.16	220.98	Chemical	4C2
							3.44	3.87	220.92	220.49	Physical	4P2

(continued)

TABLE C-8 (CONTINUED)

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of fill (m)	Elevation sludge/soil interface (m)	Sampled depth interval (m) From	To	Elevation of sampled intervals (m) From	To	Type of sample	Sample number
							5.33	5.52	219.03	218.84	Chemical	4C3
							5.58	5.88	218.78	218.48	Physical	4P3
							6.86	7.04	217.50	217.32	Chemical	4C4
							7.62	7.83	216.74	216.53	Chemical	4C5
							7.86	8.38	216.50	215.98	Physical	4P5
5	222.14	217.14	5.95	NA	NA	NA	4.88	5.06	217.26	217.08	Chemical	5C4
							5.12	5.64	217.02	216.50	Physical	5P4
6	221.17	216.17	5.85	NA	NA	NA	.30	0.49	220.87	220.68	Chemical	6C1
							0.55	1.07	220.62	220.10	Physical	6P1
							1.46	1.92	219.71	219.25	Physical	6P2
							3.57	3.96	217.60	217.21	Physical	6P3
							4.88	5.18	216.29	215.99	Chemical	6C4
7	221.49	216.25	6.16	NA	NA	NA	0.30	0.49	221.19	221.00	Chemical	7C1
							0.55	0.76	220.94	220.73	Physical	7P1
							1.22	1.40	220.27	220.09	Chemical	7C2
							1.46	1.98	220.03	219.51	Physical	7P2
							3.35	3.57	218.14	217.92	Chemical	7C3
							3.60	4.11	217.89	217.38	Physical	7P3
							4.88	5.09	216.61	216.40	Chemical	7C4
							5.12	5.64	216.37	215.85	Physical	7P4

NA = Not applicable.

Note: All elevations are given with respect to mean sea level.